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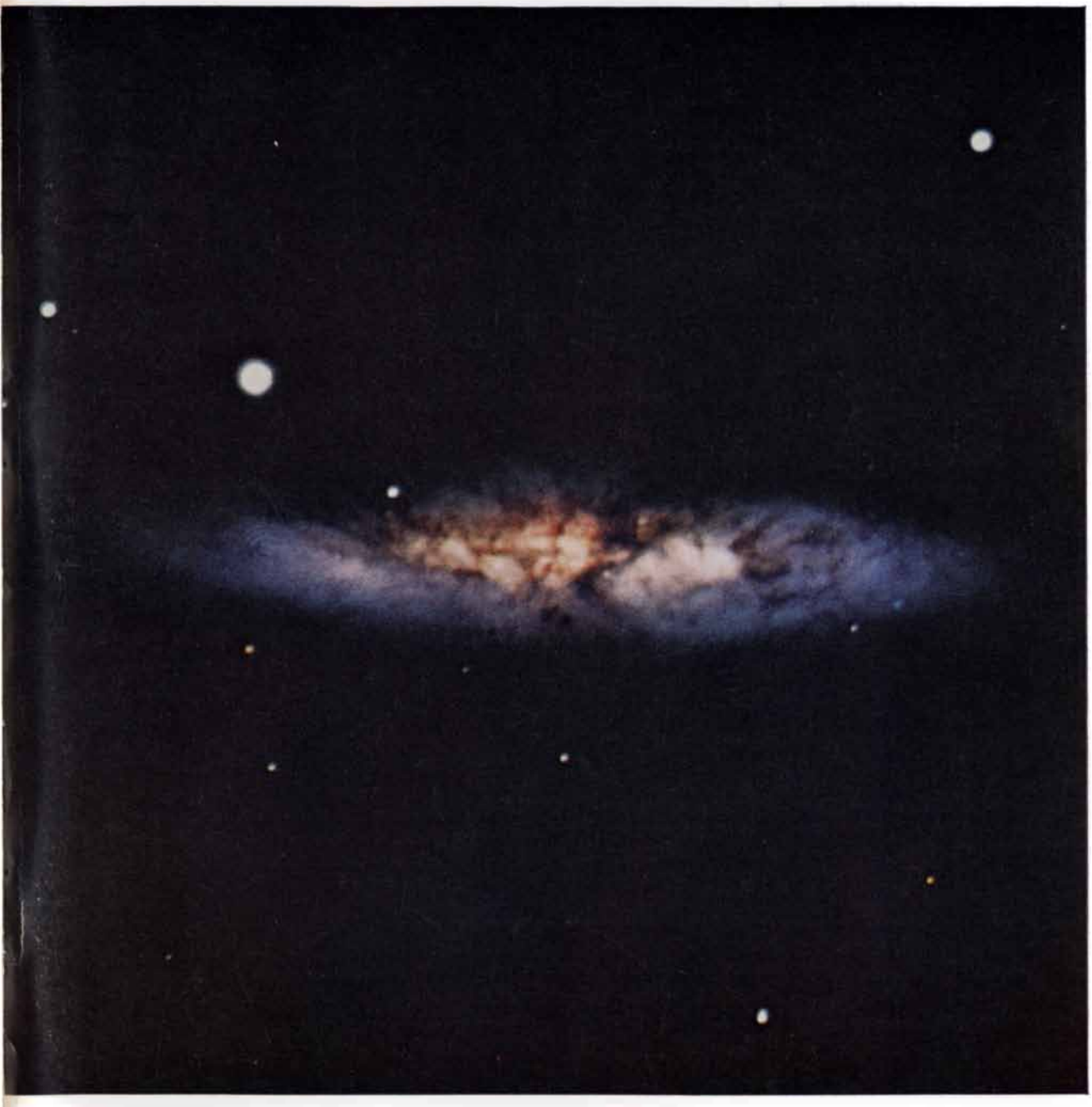
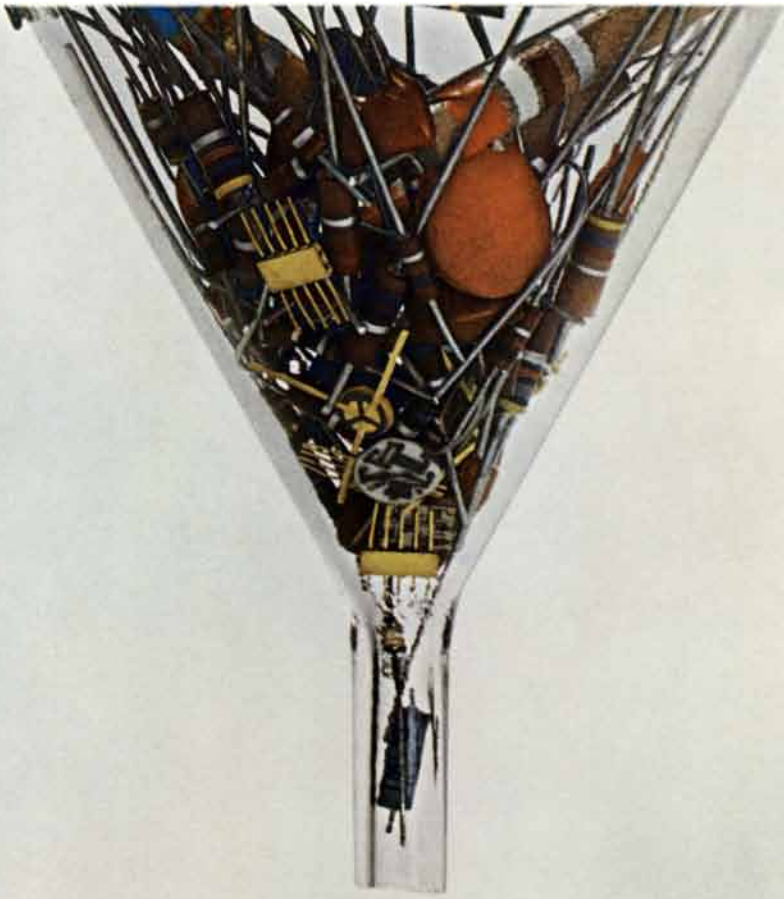


EXPLODING GALAXY

SIXTY CENTS

November 1964



Now put all these into a space

this big

Or, better yet, let us do it for you.

Amphenol systems packaging experts can rescue you from the thousand-and-one details, coordination of many suppliers, the ultimate and sticky responsibility for every stage of your system. And we can probably do it for less money and with better results than if you did it yourself.

Here's how we can help:

1. We've already helped others—in computers, aircraft, missiles, semiconductors, communications, instrumentation, controls . . . and more.

2. We are constantly handling a great variety of packaging and interconnection problems. We own virtually every kind of equipment that we (or you) might need.

3. So our engineers are not limited to any one approach. If you have to lower costs, we'll find a way to do it; if you are raising the ceiling on reliability or trying to achieve the ultimate in miniaturization, you couldn't be talking to a more savvy systems group.

4. Our men are packaging experts, familiar with the most up-to-date materials, methods, and processes as well as the old standbys.

The result? Integrated systems.

Every connection from the diode leads, through the module, the motherboard, the back panel—the complete system—is made to "play on the team." Each level of the system performs according to the original rules you set.

So talk to the man from Amphenol Microelectronics. Jack Rolf is his name. Just phone 312-345-9000. If Jack's line is busy (it often is), ask for Steve Zelencik or Lee Eichenseer.

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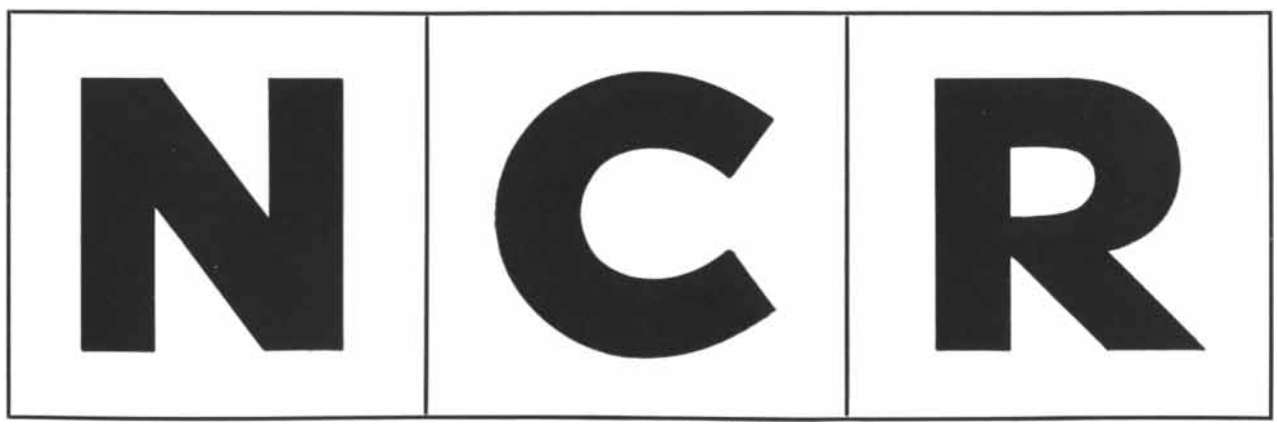
NCR announces . . . BEST (Business EDP System Technique)

New technique cuts computer programming time more than 50%

Until now, the only computer activity not measured in split seconds was programming. Programming has been complicated, time consuming and costly. But BEST changes all that. It's a completely new technique. It gets applications on the computer faster. It spells out computer instructions automatically. It can be used to quickly modify programs. And with BEST, special reports for special management meetings are no trouble at all. But just don't take our word for it . . .

Ask any computer man what it means to eliminate detailed flow charting; to eliminate detailed coding; to reduce key-punching time and errors; to minimize compilation errors. Ask him what it means to practically eliminate "debugging". And when you get the answers to these questions, you too will be excited about BEST.

BEST is a major stride in NCR's continuing software effort that supports all 315 Computers. It greatly reduces the time lag between system definition and a running computer program. For more information we urge you to act now. Simply call your nearby NCR Office. Or write to The National Cash Register Company, Dayton, Ohio 45409.



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Your watch was destined to be wrong. Accutron® is not.

Old-fashioned balance wheel is still used in all wind, self-wind, and electric watches. It is not used in the Accutron movement.

Accutron tuning fork keeps virtually perfect time and comes with the first guarantee of accuracy ever given.

Sooner or later, the watch you have is going to take more or less than 24 hours to get through the day.

This is because a watch is a small piece of machinery with parts that make other parts do things.

Now, this is a clumsy arrangement, compared to the things they're doing with electronics these days. And the Accutron movement is electronic.

A battery sends power through a circuit to operate a tiny tuning fork.

Time is kept by vibrations of this tuning fork. There are 360 of these vibrations a second, which is splitting a second into pretty small pieces.

You can imagine how precise a timepiece this makes.

We guarantee monthly accuracy within 60 seconds*—which averages out to about 2 seconds a day. Many owners say their error is only 1 second or none at all.

And now the U.S. Government is using Accutron movements in satellites and has issued them to all X-15 pilots.

They all seem to be pretty high on it.

Accutron by Bulova. Model "602" shown, 18K gold case, $300 plus tax. Others from $125 plus tax. *Your Accutron jeweler will adjust timekeeping to this tolerance, if necessary. Guarantee is for one full year. © Bulova Watch Co., Inc.

Established 1845 **SCIENTIFIC AMERICAN** November 1964 Volume 211 Number 5

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THE COVER

The photograph on the cover shows a nearby radio-emitting galaxy that has recently attracted considerable attention from astrophysicists. The galaxy is designated M 82, and this photograph of it was made with the 200-inch Hale telescope on Palomar Mountain. Other photographs, made in red and blue light with the 200-inch telescope, reveal a spectacular array of hydrogen filaments extending more than 14,000 light-years above and below the disk of the galaxy. Together with spectral measurements, these photographs are evidence that the nucleus of M 82 was the scene of a titanic explosion that occurred about 1.5 million years ago (see "Exploding Galaxies," page 38). The blueness of the north side of the galaxy's image (*bottom*) is one indication that this edge is closer to the earth than the south edge (*top*). The dark dust lanes silhouetted against the bright nucleus of the galaxy also indicate that the north edge is closer.

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Cover photograph by Allan R. Sandage, Mount Wilson and Palomar Observatories

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URGENT: Change tactical programs—in 30 seconds or less!

Suddenly, a battle alert in the field—and with it an urgent need for tactical data from the field computer. The operator presses a button, whisks out the tape cartridge he has been using, and plugs in one marked "Tactical"...all in 30 seconds or less!

A radically different, *fully militarized* digital, magnetic tape handler, developed by Sylvania, makes this quick change possible. Cartridge loading and a unique pneumatic drive eliminate manual threading and unthreading—tape is guided by suction tubes instead of spindles.

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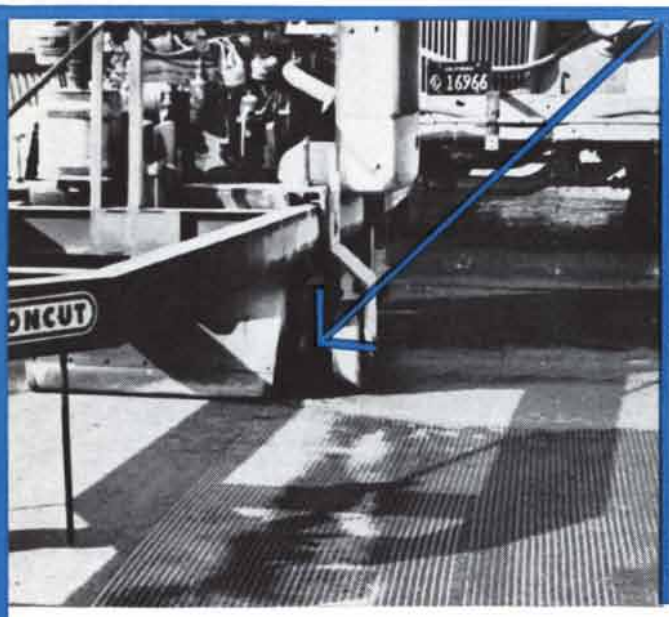
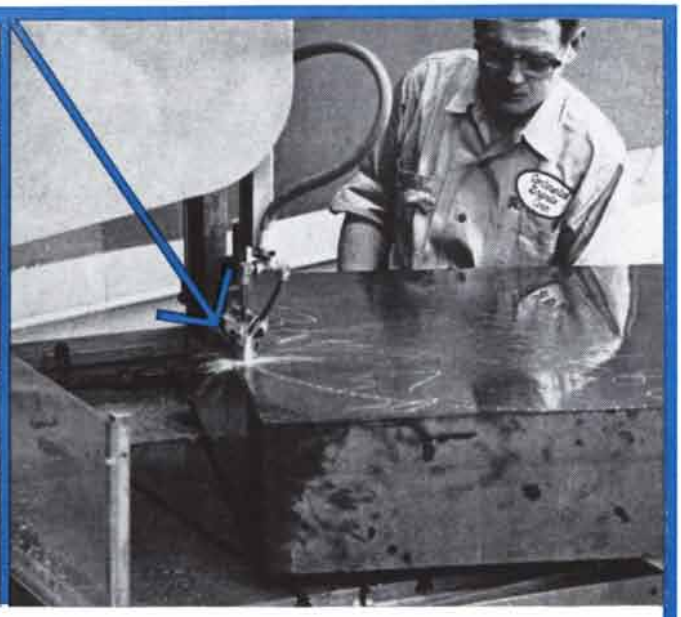




PUTTING "TREADS" ON BRIDGES

Diamond blades cut "treads" on slippery California bridge deck. Parallel grooves, ⅛ inch deep and ⅜ inch apart, are cut in pavement surface. Grooves prevent surface from becoming slick during wet weather. Cutting head, made by Concut, Inc., consists of a spindle of segmented blades containing metal-bond diamond grit.

SAWING GRANITE

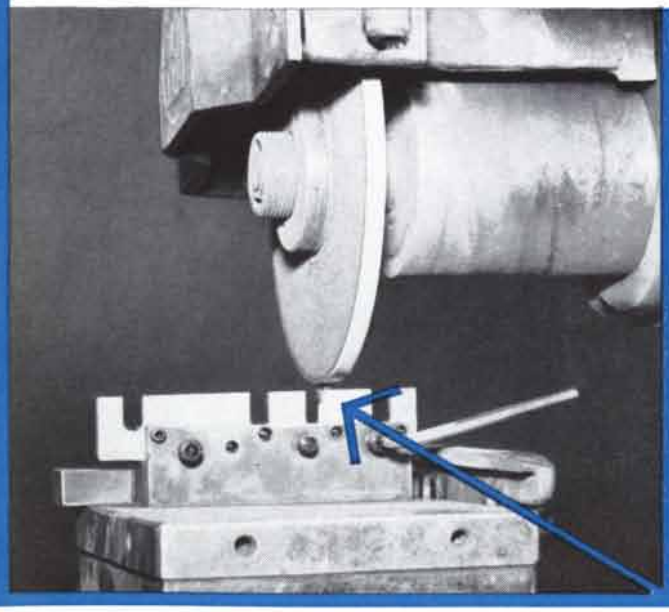
A 1250-pound block of Escondido granite is sawed with a heavy-duty, water-cooled diamond band saw at Continental Granite Corp. Finished disk will be a master flat gage. Operator controls feed of the granite into the saw with a worm-gear drive. It would be impractical to cut the 36-inch-diameter gage without diamond tools.

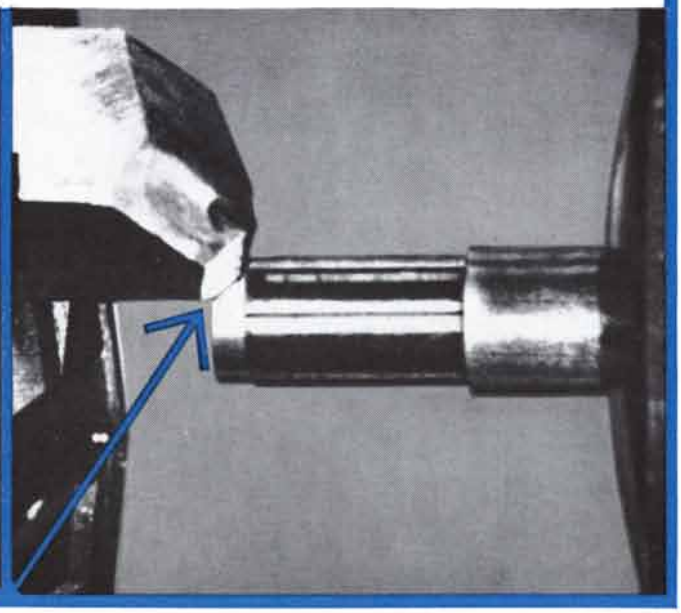
GRINDING CARBIDE TOOLS

Custom-made carbide tools are formed and ground with diamond wheels at Supreme Tri-Bit Co., Livonia, Michigan. Tolerance in this operation: .0001 inch. Careful job analysis at this plant halved cost of diamond wheels and doubled production rate at the same time.

MACHINING BERYLLIUM COPPER

to tolerances of millionths of an inch at Benrus Watch Co., Waterbury, Conn. Benrus makes a variety of components for missiles and rockets. Beryllium copper rod is first rough-cut with a carbide tool, then finished with a full-carat or larger natural diamond.





LETTERS

Sirs:

Martin Gardner's department "Mathematical Games" is the first thing we look at when we pick up a copy of *Scientific American*. His September article on puns, palindromes and other word games was quite entertaining and of particular interest to us.

In connection with the concealed message in the text *Transport Phenomena* by Bird, Stewart and Lightfoot, you might be interested to know that in the preface the first letters of the sentences actually spell "This book is dedicated to O. A. Hougen TTTM." The TTTM means "This terminates the message." Furthermore, in the forthcoming Spanish edition of our text (*Fenómenos de Transporte*), to be published by Editorial Reverté, the translator, Professor F. Mato Vázquez of the University of Salamanca, has obligingly translated our preface so that the hidden message is faithfully retained as "*Este libro está dedicado a* O. A. Hougen," with no letters such as TTTM left over. In the postface we were faced with a problem, since "On Wisconsin" would have little meaning to Spanish-speaking readers and "w" does not occur in Spanish. Hence we have requested the translator to try to include the hidden message "*Adiós amigos*" instead.

You might also be interested to know that our colleague Professor Daizo Kunii (Department of Chemical Engineering, University of Tokyo) published a book entitled *Ryudo Kahyo* several years ago. The first characters of the paragraphs in his preface spell out, in Japanese, a dedication to his wife.

R. Byron Bird

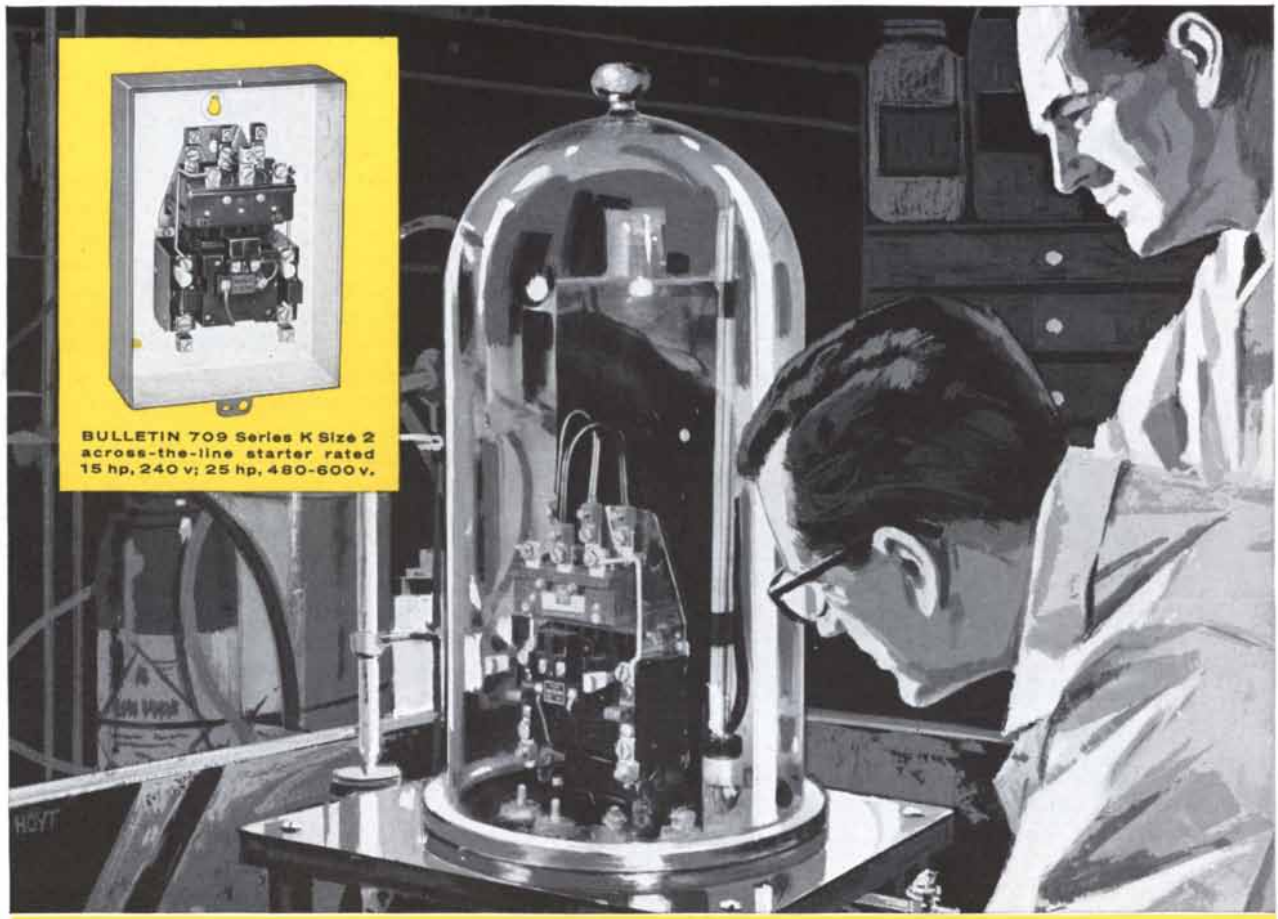
Warren E. Stewart

Edwin N. Lightfoot

Department of Chemical Engineering
University of Wisconsin
Madison, Wis.

Sirs:

In your excellent September issue on mathematics there appears an article by Philip J. Davis entitled "Number." In this article Davis declares: "The transfinite numbers have not yet found application outside mathematics itself." I would submit that if contemporary cosmology is outside of mathematics, then



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■ The most simple design possible in a starter is an important step in the direction of trouble free operation. Having only one moving part—as in the Allen-Bradley Series K control—is virtually an assurance of trouble free operation—but as moving parts increase in number, the possibilities for trouble are multiplied.

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The "finish" used on parts must take into consideration the "use" of the individual part. Keeping abreast of the constant developments in all technical fields is a "*must.*"

An example of Allen-Bradley research is the environmental gas atmosphere test illustrated above. A standard Bulletin 709 Series K starter, taken from the production line, is subjected to a high humidity atmosphere containing sulphur dioxide and chlorine at temperatures from 25°C to 40°C. At the end of the test, the starter is examined for corrosive deterioration and must pass all regular Allen-Bradley starter tests.

Such scientific studies remove the "guesswork" in selecting compatible combinations of materials and coatings. Allen-Bradley engineers "know" that the Series K controls will retain their quality appearance and quality performance, even under abnormal conditions. There may have been a time when control apparatus could be "hammered" together, but only the control that is backed with adequate research can keep abreast of the needs of today. Please visit our laboratories—you will then understand why Allen-Bradley is "tops" in motor control.

The A-B distributor in your area is factory-trained, and will be happy to give you full technical details. Contact him today, or write for Publication 6100: Allen-Bradley Co., 1204 S. Third Street, Milwaukee, Wisconsin 53204.

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we can find an excellent application of Cantor's transfinite numbers.

One allowable and very useful cosmological model provides for an infinite number of separate galaxies, located throughout infinite space (Euclidean or Lobachevskian). These galaxies are conceived of as receding from each other (if not too close) with radial speeds proportional to their radial distances from each other (Hubble's law). The question is: How can an infinite number of galaxies have any more room to separate from each other? One answer that can be given is that the number of galaxies is a *denumerable* infinity (aleph sub zero), whereas the infinity of loci in space is a *nondenumerable* infinity (presumably aleph sub one)—which is a *larger* infinity—so there is plenty of room for expansion of such a universe, in spite of any intuitions to the contrary.

CARLTON W. BERENDA

Department of Philosophy
University of Oklahoma
Norman, Okla.

Sirs:

The article on computers by Stanislaw Ulam in your issue on mathematics states that it is not known if the Fermat number with an n of 13 is a prime.

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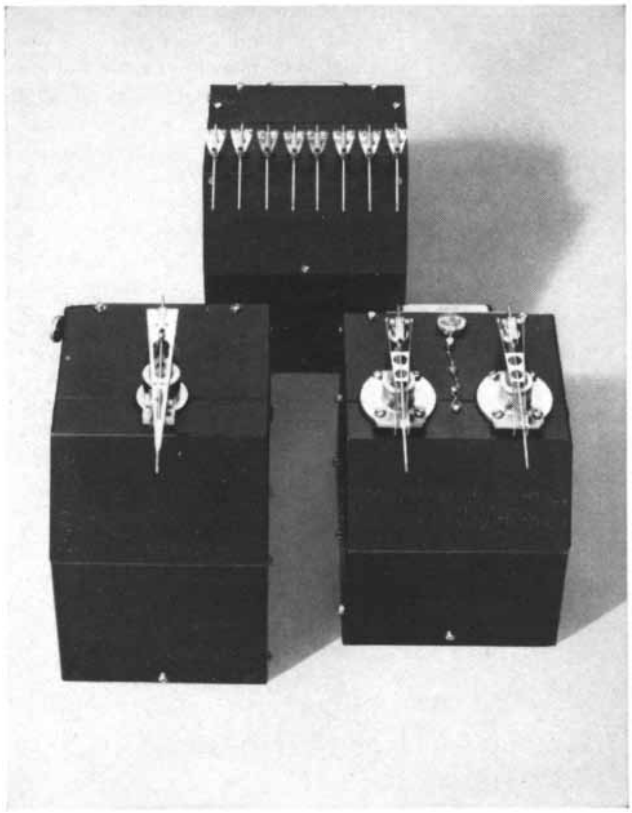
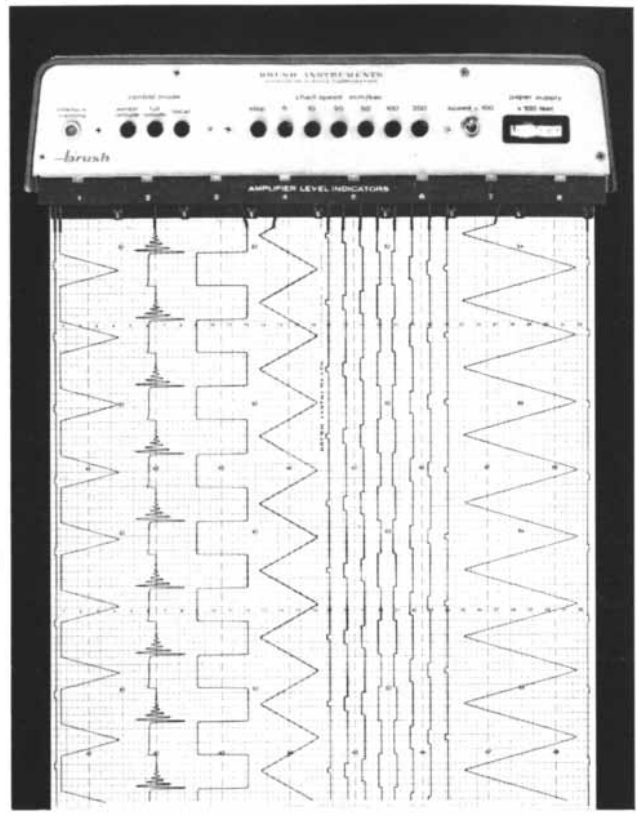


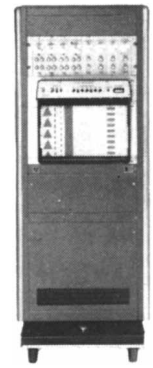


These are Optional Penmotors for the Brush Mark 200 Series 1707 Recorders

You should see the information they give ...in combination!

(modern oscillography will never be the same)

Optional penmotors are the newest of several Brush innovations that change previous notions about today's direct writing recording. The pace-setting Mark 200 now gives you any combination of variables . . . 80mm channels for extreme resolution in absolute measurement . . . 40mm channels for coordination of dynamic information . . . "yes-no" information from time-codes, relays, actuators, etc. *One recorder presents them all . . . in any combination . . . on the same chart . . . on a common time base!* The choice is yours! And, a pressurized inking system with over 10,000 channels of performance produces traces so accurate and crisp that you can't misread the signal. *True* rectilinear motion results from a unique linkage that creates a straight line 99.9% accurate. A super-sensor called the Metrisite "polices" the pen position for instant self-correction without mechanical restraint. The rule book of oscillography *is* changed. Check Brush for *new* standards. Your letterhead request will bring the complete story.



brush INSTRUMENTS

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(Fermat numbers are numbers of the form $2^{2^n} + 1 = F_n$.)

On the contrary, the Fermat numbers with n equal to 13, 14, 15 and 16 are known to be not prime. G. A. Paxson tested F_{13} ("The Compositeness of the Thirteenth Fermat Number." G. A. Paxson in *Mathematics of Computation*, Vol. 15, page 420; 1961). J. L. Selfridge and I tested F_{14} on the U.C.L.A. Computing Facility's IBM 7090 ("Fermat Numbers and Mersenne Numbers." J. L. Selfridge and Alexander Hurwitz in *Mathematics of Computation*, Vol. 18, page 146; 1963). The numbers F_{15} and F_{16} are known to have small factors.

It is not known whether F_{17} is prime or not. It would take approximately 21,500 hours of 7090 time to perform the same test on F_{17} as was performed on F_{13} and F_{14}.

ALEXANDER HURWITZ

U.C.L.A. Computing Facility
University of California
Los Angeles, Calif.

Sirs:

If I were B. F. Skinner I would be content with Jules Henry's reply to his letter in your September issue. Henry—who showed in his earlier review that he did not know the facts with respect to Skinner boxes—now shows that he does not understand the ideas (and the supporting evidence) in a wider field: the relation of man's behavior to that of lower animals. On what basis does he regard it as self-evident that animals have no "ideas" and that "thought" can only be investigated in man? Hobhouse, Köhler, Yerkes, Lashley, Tolman—what a row of distinguished witnesses could be called for the defense!

One need not agree with Skinner in all matters in order to recognize the brilliance constituted by the paper that showed an identity in certain behavior of the pigeon and human superstitious behavior: a genuine insight into the thought processes of man. It is true that there are great differences in the concomitant details, man's behavior being so much more complex; but the central mechanisms may be as much the same as, for example, the mechanisms of reproduction in these two widely different species.

D. O. HEBB

Department of Psychology
McGill University
Montreal, Canada

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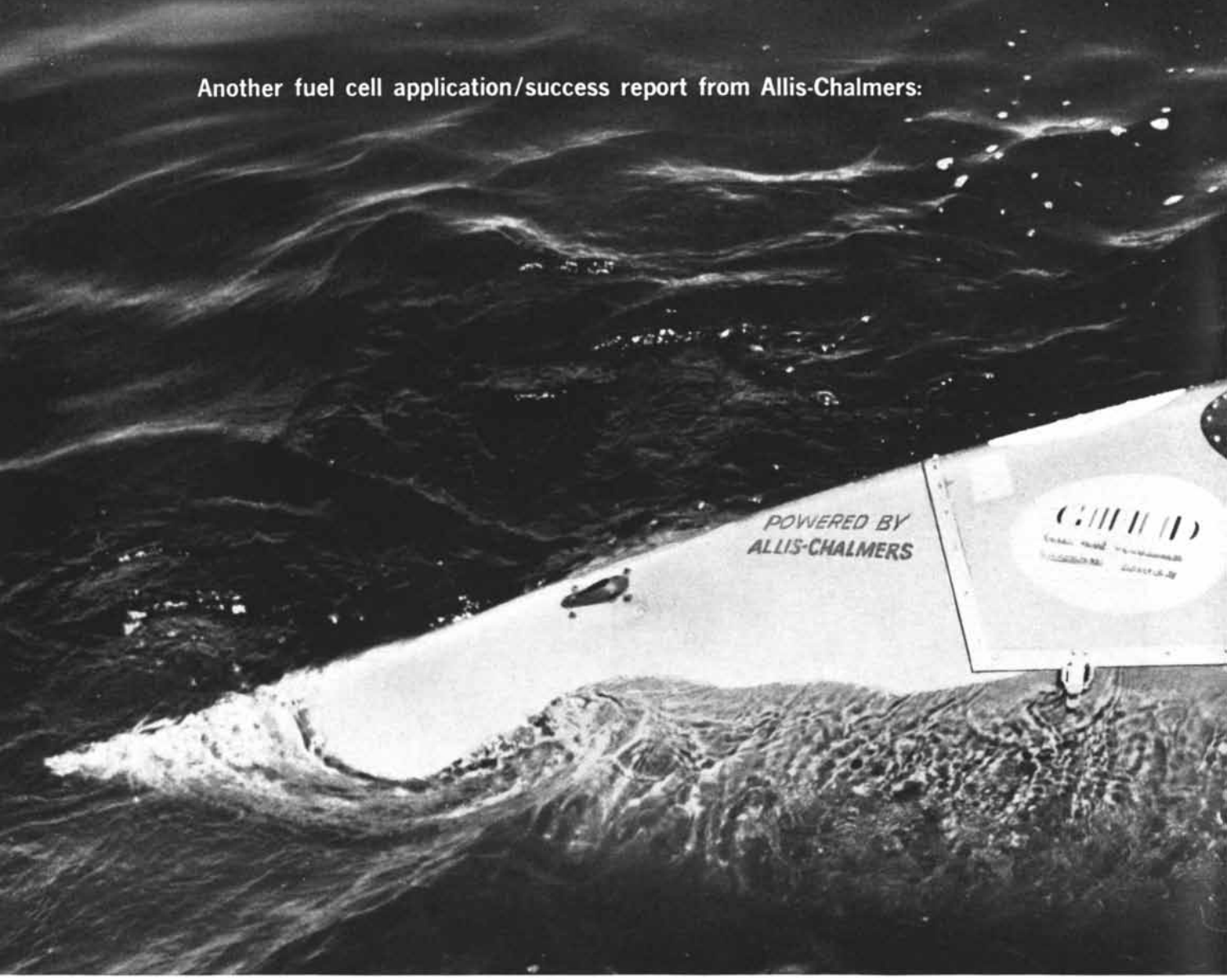


World's first fuel-cell operated submarine!

July, 1964, Groton, Conn.: Star I — a one-man test and research submarine — was successfully operated both submerged and on the surface. An Allis-Chalmers 36-volt fuel cell produced 750 watts to power the vessel's electric drive motors, communications, navigation, life support and lighting equipment.

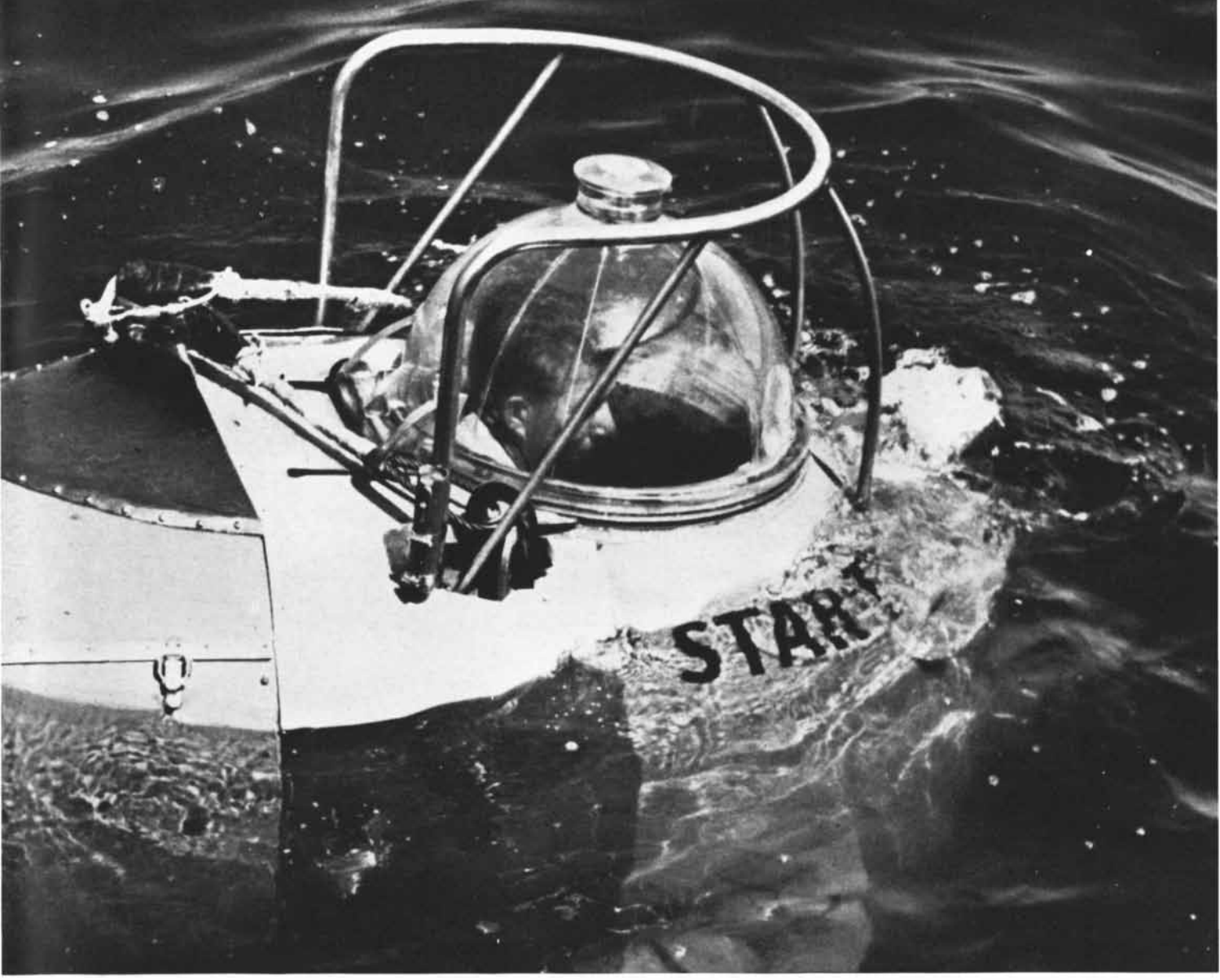
Star I — owned and operated by General Dynamics/Electric Boat Division — was powered by an Allis-Chalmers fuel cell system. It is a nine-foot-long, teardrop shaped 2,500 lb. submarine. A-C and Electric Boat Research engineers teamed up to successfully adapt fuel cell power to the submarine. Purpose: **to extend the vessel's capabilities beyond those of conventional storage battery power.**

In effect what the fuel cell has demonstrated was to double the Star I's endurance time. Previously batteries lasted up to 4 hours and required 8 hours to recharge. In the fuel cell, endurance is measured by the quantity of fuel and oxidant aboard and only five to ten minutes are sufficient to change to a fresh supply of hydrazine (the fuel) and oxygen (the oxidizer).

And this new Allis-Chalmers fuel cell application follows on the heels of A-C's 14 lb. hydrogen-oxygen fuel cell developed for the Air Force. This cell qualified for orbiting. It's scheduled to produce electrical power for systems aboard aerospace vehicles.

May we discuss your aerospace or defense fuel cell application? TELEPHONE AREA CODE 414-774-3600, EXT. 491, ALLIS-CHALMERS, Box 512, Milwaukee, Wis. 53201. A-1939

ALLIS-CHALMERS



The compact Allis-Chalmers fuel cell is ready for lowering into the non-pressurized glass fiber fairing behind the STAR I's four-foot spherical pressure hull.

In July, 1964, the 9-foot long STAR I, powered by A-C fuel cells, operated successfully both submerged and on the surface.

Quick summary:
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. . . in a land vehicle, a 15-kw tractor 1959

FIRST
. . . to successfully pass zero gravity tests, Wright Patterson AFB 1961

FIRST
. . . "qualified for space" fuel cells for the Air Force. . . . March, 1964

FIRST
. . . to power an underwater vehicle . . . . . July, 1964

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

NOVEMBER, 1914: "A few weeks ago, and fully two weeks before the loss became known to the public, the British dreadnought *Audacious,* one of the four ships of the *King George V* class, struck a mine off the north coast of Ireland and went to the bottom. The sinking of the *Audacious* is by far the most serious loss yet sustained by any of the naval powers engaged. In fact, in its bearing upon the actual fighting strength of the British navy it is equal to the sum of all the losses previously suffered. The *Audacious* was a capital, or first-line, ship, one of those major units which must line up against the enemy in that supreme and decisive engagement (if it ever takes place) when the German battleship fleet emerges to fight it out in a great fleet action."

"The researches of Schumann enabled him to extend the spectrum to about 1,250 angstrom units and subsequently Mr. T. Lyman continued it to 1,030 angstroms by the use of a concave grating. Now Mr. Lyman has succeeded in photographing the spectrum of hydrogen to 905 angstroms. It is characteristic of the region investigated by Schumann between 1,850 and 1,250 angstroms that, whereas hydrogen yields a rich secondary spectrum, with the possible exception of one line no radiation has been discovered belonging to the primary spectrum. On the other hand, in the new region between the limit set by fluorite and 905 angstroms, a disruptive discharge in hydrogen produces a primary spectrum of great interest made up of perhaps a dozen lines. It may be stated with some degree of certainty that the diffuse series predicted in this region by Ritz has been discovered."

"It is suggested that some of the striking changes manifested by certain comets in executing their orbits are due to the fact that they encounter masses of gas in interplanetary space and that they are not moving in a vacuum. If there are such gaseous masses, then in view of the inclinations and extent of their orbits, comets are peculiarly fitted to act as explorers and there is every probability that they would sooner or later encounter such masses. Many phenomena seem to receive a satisfactory explanation if the existence of gaseous masses scattered through the solar system be admitted. These gaseous masses may be considered as the residue of the initial nebula, having escaped the phenomenon which gave rise to the other members of the solar system."

"John Stasiak of Seattle, Wash., has patented an aeroplane especially designed for use in war. It has an automatic control mechanism which can be set when the device is started on its journey and which predetermines the length of the journey, at the end of which automatically operating means drop a bomb and automatically reversing and returning means are brought into play to return the aeroplane to its starting point and to shut off the power when such starting point is reached on the return."

Scientific American.

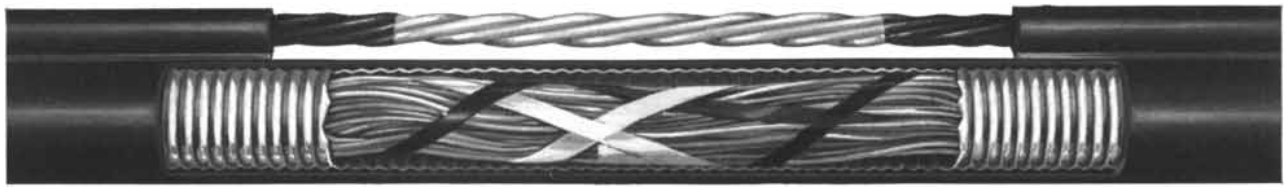
NOVEMBER, 1864: "Abraham Lincoln of Illinois has been re-elected President by a large popular majority. Andrew Johnson of Tennessee has been chosen Vice President, to succeed Hannibal Hamlin of Maine. The election passed off peaceably and without the necessity of military interference, and it now becomes citizens of all parties to yield a willing and cheerful obedience to the authorities thus constituted by the popular suffrage. We have already witnessed the direful consequences of a rebellion against the rightfully chosen leaders of the nation, the sad effects of which will exist for a generation at least. We therefore exhort our readers to put aside all partisan bitterness and yield unwavering devotion to the Government. This war would, in our judgment, come to a speedy end if citizens of every class would unite in strong determination to succeed. We have a country and a government worth saving, and it cannot be rescued from destruction by sharp partisan conflicts, such as we have now most happily passed through."

"The rebel ram *Albemarle* was destroyed on the 28th ult. by a torpedo,

Report from

BELL LABORATORIES

"UNDULATED" CORE MAKES SELF-SUPPORTING CABLE PRACTICAL



ABOVE: Drawing of new self-supporting cable structure shows "undulated" core of telephone wires encased in aluminum and polyethylene sheath members. Edges of corrugated aluminum sheath are butted along top of cable. Polyethylene sheath extends over steel strand on top to provide built-in cable support. BELOW: Photographs show, left to right, older-type ring-supported cable, present lashed cable, and new self-supporting cable.

Telephone cables strung along pole lines need mechanical support. Heretofore, this support has been provided by a separate, strong steel strand from which the cable is suspended—either by wire rings or by a lashing wire wound helically around the strand and cable.

For ease of installation it is desirable to design the cable and strand into a single self-supporting structure. But in such designs the cable sheath and its core of telephone wires, as well as the strand, may be placed under tension when suspended between poles. With the wires under tension, craftsmen have no readily available slack wire, which is needed in making connections for bringing service to a customer's house.

To solve this problem Bell Laboratories engineers, working in close cooperation with engineers of the Western Electric Company, manufacturing unit of the Bell System, "built the slack into the cable." The slack is provided by an undulation incorporated into the core of telephone wires. To help prevent the polyethylene cable sheath from tightening around the wires during manufacture, the longitudinal edges of a corrugated aluminum sheath member are butted up against each other, rather than overlapped as in other cables.

The new cable permits both efficient and economical construction methods. It is rapidly raised, tensioned, and clamped to poles. Craftsmen easily pull slack wire from the cable and, using plastic "ready access" terminals, make the required connections.

Bell Telephone Laboratories
Research and Development Unit of the Bell System

which was placed in position by a method that has been frequently recommended in the SCIENTIFIC AMERICAN. This method is to attach the torpedo to a boom extending forward from the bow of a swift vessel. The *Albemarle* was an enormous iron-clad ram, said to be far more powerful than the *Merrimac* or the *Tennessee*. She was lying in the Roanoke River at Plymouth, surrounded by a crib of logs arranged to protect her from rams and torpedoes. The desperate enterprise of attempting the destruction of this great ship of war with a small steam launch and 13 men was undertaken by Lieut. W. B. Cushing of the Navy. Selecting a dark, stormy night, he proceeded silently up the river and, driving the bow of his vessel among the logs that surrounded the *Albemarle*, he lowered the boom and by a vigorous effort pushed the torpedo under the overhang of the ram and exploded it. Never before in the history of naval warfare has there been a battle at such odds as this. The *Albemarle* is the second great rebel ram that has been disabled by a single shot."

"Since our last mention of the 20-inch gun the carriage has been completed and the gun mounted. On Wednesday, the 25th of October, this cannon was loaded and fired with the largest charge of powder and the heaviest shot that has ever yet been discharged from any piece of ordnance. For this trial a charge of 100 pounds of powder was placed below a solid ball of cast-iron weighing 1,080 pounds and the gun was elevated at an angle of 25 degrees. At the report the ponderous globe rushed up through the air with a hoarse roar and fell a great distance—estimated at 3½ miles—into the sea. The report of the gun was not perceptibly louder than that of moderately large ordnance, and the concussion produced no extraordinary trembling of the earth. There is no doubt, however, that the half tun of cast-iron which this gun hurls forth would have more effect in crushing in the sides or deck of an iron-clad ship than any other missile that has ever been wielded by human skill."

"The captain of a vessel direct from Glasgow, Scotland, says there are hundreds of steamers building and fitting out in the Clyde and adjacent waters, all to run the blockade. They act as if the war were to last for the next five years. He says every shipbuilder on the Clyde has gas-lights in his yards and, with relays of hands, works every hour of the 24."

HOW SMALL WILL OUR WORLD BE?

In just the time since most of us were youngsters, the great wide wonderful world has been shrunk to the size of a television screen. Dial the Olympics in Tokyo, on-the-spot reports of news, the recovery of a space vehicle, the antics of your favorite comedians . . . .

A system of orbiting satellites is enabling electronics communications to bring the whole world home to you. The pictures reach you with the speed of lightning. The world measures 19 or 21 inches. And the technological miracle is still in process of development.

Since its beginnings in the 1920's when WLW pioneered broadcasting in Cincinnati, Avco's subsidiary, Crosley Broadcasting, has been associated with mass communications. Crosley increased its WLW wattage from a mere 50 to 50,000 in six years. It has achieved, experimentally, broadcasting with a wattage as high as 500,000. Crosley also helped introduce FM, scheduled TV, and color TV.

In addition to commercial broadcasting, Crosley has raised millions of dollars for charity, contributed materially to the founding of educational channels, and established a documentary unit of award-winning quality for the production and telecasting of public service programs.

Crosley broadcasts with a worldwide point of view through its national affiliations. But it also localizes its broadcasting with an independence reflective of an American town meeting.

Avco means leadership in broadcasting, aircraft engines, farm equipment, and space and defense research, development, production. If you are interested in a career at Avco—an Equal Opportunity Employer—please write us.

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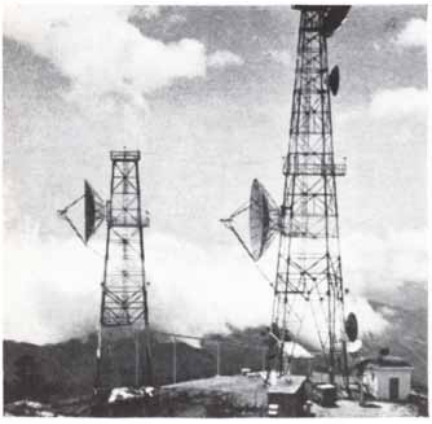
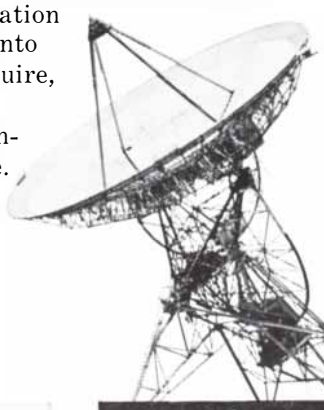
Experience means the world to Collins



Throughout the Free World, Collins is *applying* Information Science . . . combining automatic communication, computation and control equipment into total systems which acquire, transfer, store, extract, process and condense information for man's use.



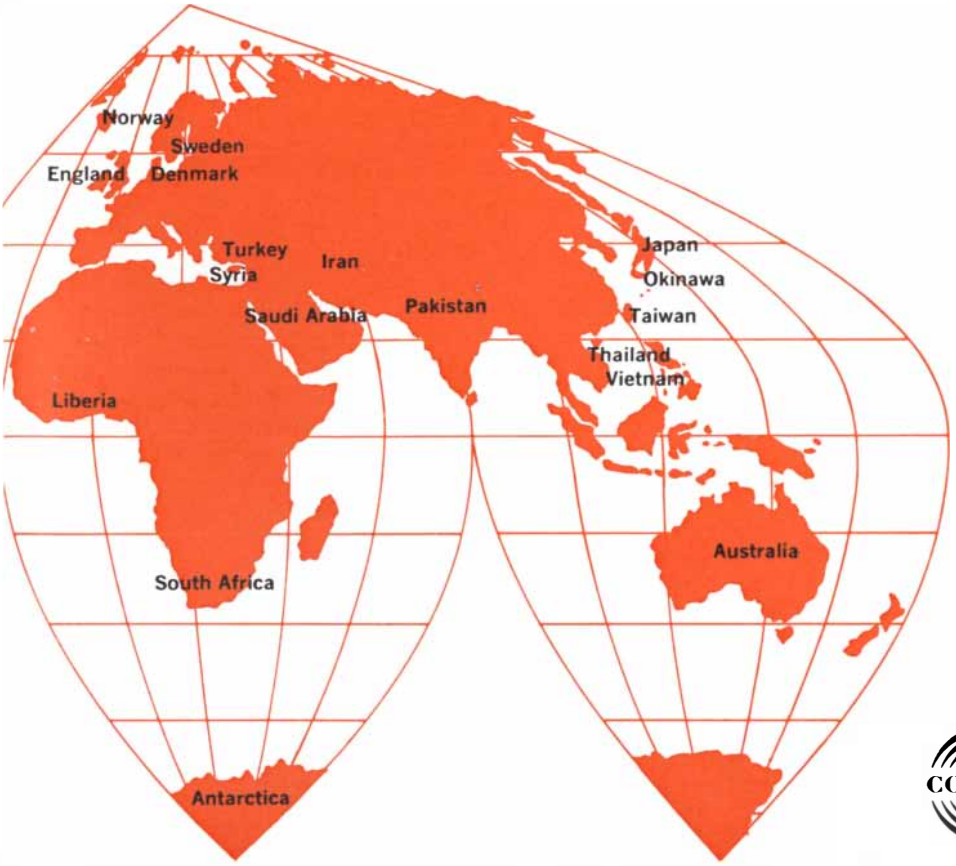
IN OKINAWA . . . A scatter communication system linking this island with the rest of the world.

IN VENEZUELA . . . Microwave and scatter communication systems provide reliable 24-hour telephone and teletype service.

IN AUSTRALIA . . . Space-tracking system for acquisition and use of data from space vehicles.

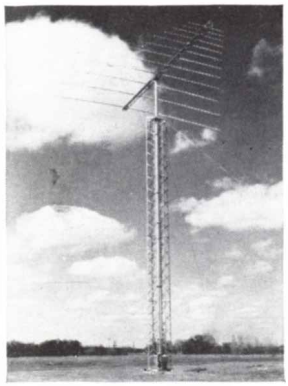
IN TAIWAN . . . Microwave communication and control system encircling the 200-mile-long island of Formosa.

IN CANADA . . . Airline communication/computation/control systems; data system for control of telecommunication company; microwave in railroad operations; high frequency radio telephone network.



COLLINS

COMMUNICATION / COMPUTATION / CONTROL COLLINS RADIO COMPANY / WORLD HEADQUARTERS / DALLAS, TEXAS



IN NORWAY . . . Automatic communication system reaching from Oslo north of the Arctic circle; assures constant contact between NATO's North Atlantic land and sea forces.

IN THE U. S. A. . . . The world's leading supplier of aviation electronics; the world's largest data communication center; communication/control systems for Mercury, Gemini, Apollo; data centers for airlines, railroads and other commercial business; microwave communication and control for pipelines, railroads, telephone, television, air traffic; commercial broadcast systems; virtually every conceivable form of electronic communication / computation / control for all of the U. S. Armed Forces.

IN SAUDI ARABIA . . . High frequency network supplies weather and operational information for airline operations.

IN SYRIA . . . Microwave system linking such ancient cities as Damascus, Aleppo and Latakia with telephone, telegraph and commercial broadcast service.

IN THAILAND . . . Microwave system delivers telephone communication over 1100 route miles to 22 cities and 22 million people.

THE AUTHORS

RICHARD S. MACNEISH ("The Origins of New World Civilization") is chairman of the department of archaeology at the University of Alberta. A native of New York City and a former Golden Gloves boxing champion, MacNeish was graduated from the University of Chicago in 1940. He went on to acquire an M.A. in anthropology and a Ph.D. in archaeology, physical anthropology and ethnology from Chicago in 1944 and 1949 respectively. Since 1936 MacNeish has participated in more than 40 archaeological field expeditions to various sites in the U.S., Canada and Mexico, and he has written more than 100 books, articles and reviews on New World archaeology. From 1949 to 1963 he was chief archaeologist for the National Museum of Canada. He has led four expeditions in the past four years to the valley of Tehuacán in southern Mexico on behalf of the Robert S. Peabody Foundation for Archaeology; the results of these expeditions form the basis of the present article.

ALLAN R. SANDAGE ("Exploding Galaxies") is an astronomer at the Mount Wilson and Palomar Observatories. A graduate of the University of Illinois, Sandage received a Ph.D. in astronomy from the California Institute of Technology in 1953. He has worked at Mount Wilson and Palomar since 1952. In 1960 he was awarded the Helen Warner prize of the American Astronomical Society and in 1963 he won the Eddington Medal of the Royal Astronomical Society.

DANIEL S. LEHRMAN ("The Reproductive Behavior of Ring Doves") is professor of psychology and director of the Institute of Animal Behavior at Rutgers University. Lehrman was graduated from the City College of the City of New York in 1947 and obtained a Ph.D. in psychology from New York University in 1954. He has been a member of the Rutgers faculty since 1950.

M. F. PERUTZ ("The Hemoglobin Molecule") is chairman of the Laboratory of Molecular Biology in Cambridge, England. Perutz was born in Vienna in 1914 and did his undergraduate work in chemistry at the University of Vienna. In 1936 he went to England to do research under J. D. Bernal at the Cavendish Laboratory of the University of Cambridge. He received a Ph.D. in X-ray crystallography from Cambridge in 1940. From 1939 to 1945 he worked as a research assistant to W. L. Bragg at the Cavendish Laboratory. In 1947 Perutz was made director of the newly constituted Medical Research Council Unit for Molecular Biology, a post he held until 1962, when the Medical Research Council built the Laboratory of Molecular Biology for him and his colleagues. Perutz' work on the structure of hemoglobin, he writes, "started as a result of a conversation with F. Haurowitz in Prague in September, 1937. G. A. Adair made me the first crystals of horse haemoglobin and Bernal and I. Fankuchen showed me how to take X-ray pictures and how to interpret them. Early in 1938 Bernal, Fankuchen and I published a joint paper on X-ray diffraction from crystals of haemoglobin and chymotrypsin. The chymotrypsin crystals were twinned and therefore difficult to work with, and so I continued with haemoglobin." It was not until 15 years later, in 1953, that Perutz finally discovered a method for solving the structure of the protein molecules. His method led to the solution of the structure of myoglobin by John C. Kendrew and of the structure of hemoglobin by Perutz himself. For these discoveries Perutz and Kendrew were awarded the Nobel prize in chemistry in 1962. On that occasion Perutz remarked: "I have had the good fortune of being joined by colleagues of great ability, several of whom have now been honored with the Nobel prize at the same time as myself. Kendrew came in 1946, [F. H. C.] Crick in 1948, and [J. D.] Watson arrived as a visitor in 1948. Recently F. Sanger, who received the Nobel prize in 1958, also joined forces with us. I am extremely happy at the generous recognition given by the Royal Caroline Institute to our great common adventures and hope that it will spur us to new endeavours."

BERNHARD WUNDERLICH ("The Solid State of Polyethelene") is associate professor of physical chemistry at the Rensselaer Polytechnic Institute. A native of Germany, Wunderlich was graduated in 1953 from Goethe University in Frankfurt. After obtaining a Ph.D. from Northwestern University in 1957 he taught at Northwestern and at Cornell University until 1963, when he was appointed to his present post.

MARY MCNEIL ("Lateritic Soils") is a geologist on the staff of the Lockheed-California Company, a division of the

NEWS
from
RESEARCH LABORATORIES
Ford
MOTOR COMPANY

Ford Motor Company develops experimental gas turbine superhighway hauler to anticipate national highway network of the 1970's

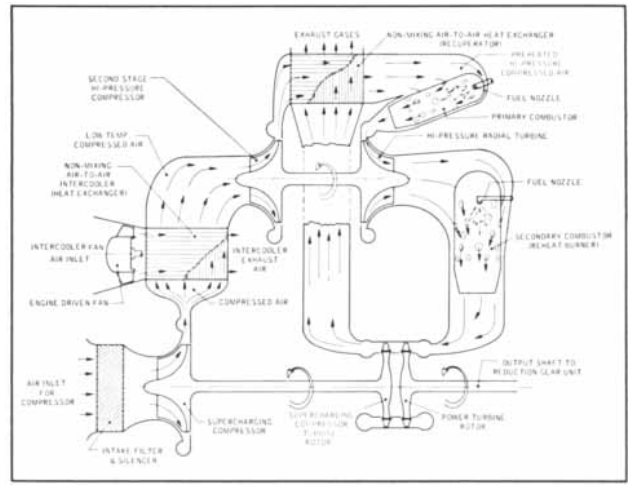
Looking ahead to the completion, in the 1970's, of a 41,000-mile network of national and interstate freeways, Ford Motor Company is already investigating new vehicles to match the highway system.

One such vehicle, an experimental superhighway truck, has been developed by the Ford Research Laboratories as part of the Concept Car Program which entails the design and fabrication of advanced, functional, experimental vehicles.

Heart of the experimental truck is the 600 hp Ford 705 gas turbine engine. A unique feature of the 705 turbine is its supercharger. The supercharging cycle comprises two compression stages using centrifugal compressors. Exhaust gases are routed through a recuperator to preheat air entering the primary combustor. The design permits a weight-to-power ratio one-third that of comparable diesel engines. Virtually two engines in one, the 705 turbine develops 45 hp for stand-by and auxiliary power with only half of the engine operating. By pushing a reset button, the supercharger is activated and the full 600 hp is available. A prime purpose of the experimental truck is to provide evaluation studies of over-the-road turbine performance.

As a rapid-transit hauler of freight and cargo, the superhighway truck is unique in many respects. Gas turbine efficiency will permit a non-stop range of 600 miles at cruising speeds of 70 mph and sustained 24-hour-a-day operation. This will make the truck compatible with the normal traffic flowrate of passenger vehicles. The truck is extremely quiet on the road; the loudest noise at top cruising speed is that of the tires. This, combined with its clean, quiet, odorless exhaust will afford further compatibility with high-speed passenger car traffic.

Designed for non-stop, long-distance operation, the two-man cab includes a fold-away table, lavatory, toilet, oven, refrigerator, a television set for the co-driver and a heating and air conditioning system. Cab roof is 13 feet from the ground, permitting excellent visibility from the cab. Interior headroom is 6′ 3″.



This experimental vehicle is just one expression of our confidence in the future of the gas turbine. Ford Motor Company has also embarked on a multimillion dollar expansion program calling for greatly increased facilities, more turbine specialists and further research into the growing potential of turbines.

PROBING DEEPER TO SERVE BETTER

Ford
MOTOR COMPANY
The American Road, Dearborn, Michigan

Lockheed Aircraft Corporation. A graduate of Arizona State University, she obtained an M.A. in geology from the University of California at Los Angeles in 1963; she is currently working for a Ph.D. in geography at U.C.L.A. She has worked for much of the past 12 years as a professional field geologist in Latin America and Africa. From 1952 to 1956 she was employed by the National Economic Council of the Brazilian government. Since joining the Systems Research Division of Lockheed-California in 1960 she has done research in several fields, including oceanography, geophysics and geography.

R. S. SHANKLAND ("The Michelson-Morley Experiment") is Ambrose Swasey Professor of Physics at the Case Institute of Technology. A Case graduate, Shankland received a Ph.D. in physics from the University of Chicago in 1935. His doctoral thesis, under Arthur H. Compton, was on certain aspects of the Compton effect. He joined the Case faculty in 1930 and was appointed to his present post in 1941. During World War II he worked on developing sonar and was director of the U.S. Navy Underwater Sound Reference Laboratories.

JOHN COHEN ("Psychological Time") is professor of psychology at the University of Manchester. He acquired his degrees from University College London, where from 1933 to 1940 he did research under Cyril Burt on the application of factor analysis to human intelligence, physique and temperament. In 1940 he joined the Institute for Experimental Psychology at Oxford University. During World War II Cohen served as secretary of a committee that prepared a report for the British government on the effectiveness of psychologists and psychiatrists in the armed services. In 1948 he was appointed technical secretary of the International Preparatory Commission for the World Congress on Mental Health. During this period he was also a consultant to the World Federation on Mental Health and to UNESCO. After teaching for a year at the University of Leeds he was appointed professor of psychology at the Hebrew University in Jerusalem. He taught for another year at the University of London before joining the Manchester faculty in 1952.

GEORGE A. MILLER, who in this issue reviews Arthur Koestler's *The Act of Creation*, is professor of psychology at Harvard University.

CERAMIC ENGINEERS AT HOMER LAUGHLIN MIX IMAGINATION WITH ALCOA ALUMINAS

RELAX!

It's Homer Laughlin China

The uncommon strength of Homer Laughlin chinaware has hotel and restaurant men shaking their heads—and smiling all over. Sure, you can break these plates, but you have to work at it.

Produced by The Homer Laughlin China Company, Newell, W.Va., pioneer in the use of aluminas for institutional china, this remarkable dinnerware is made with Alcoa® Alumina. And that's the difference.

Specifically, alumina content increases the fired whiteness of vitreous china; increases mechanical strength remarkably, particularly resistance to chipping; and increases the firing range of the body.

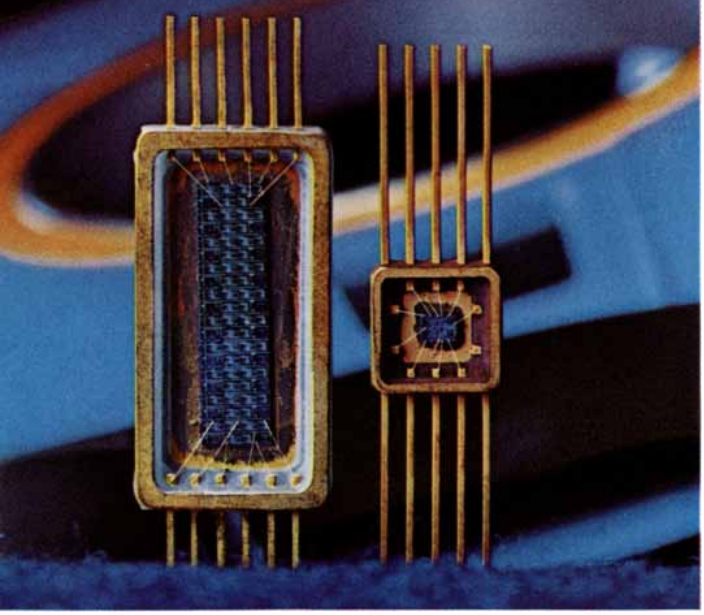
Today, ceramic engineers employ the special properties of Alcoa Aluminas to make a wide variety of things harder and stronger—nose cones, electronic parts, refractories, cutting tools, bearings, insulators, even gyroscopes. There's no foreseeable end to the list.

Fortunately, Alcoa Aluminas are readily available in large quantities at reasonable prices. Please write for our booklet, *Ceramics — Unlimited Horizons*. It will likely spark an idea for your next ceramic project. Aluminum Company of America, 840-L Alcoa Building, Pittsburgh, Pa. 15219.

Alcoa Brings You America's Finest News Show...
THE HUNTLEY-BRINKLEY REPORT, on NBC-TV

ALCOA

In electronics, things

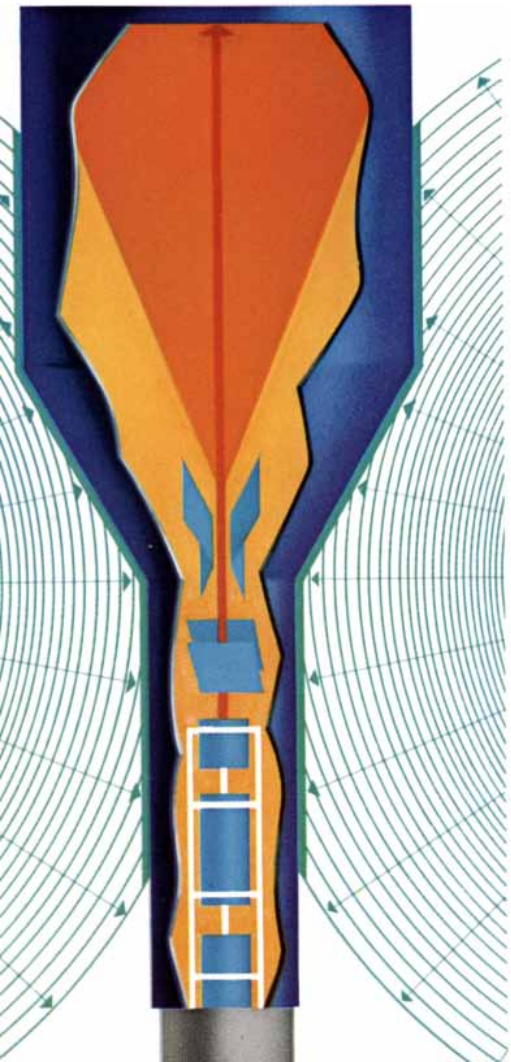


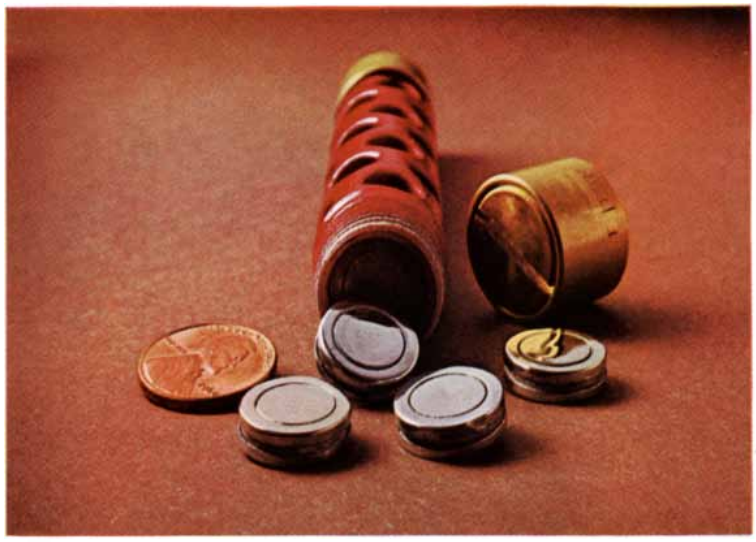
Inside look at two generations of integrated circuitry. Integrated-circuit technology now makes it possible to put an entire computer subfunction of up to 1800 gates on a single slice of silicon (above left). The full potential of this revolutionary concept will be realized once some thorny packaging problems have been overcome. In the meantime, we routinely produce in volume integrated circuits containing as many as 46 individual components (above right). These devices offer the highest noise margin in the industry, plus extremely fast switching speeds—two reasons why they have been so widely accepted for major commercial and aerospace applications.

Fiber-optic tube transfers radar images to film with extreme fidelity.

With no intervening lenses to add weight, volume and light-transmission loss, this new Westinghouse fiber-optic tube puts the single-line scans from high resolution radars directly onto film—producing permanent records of near-photographic quality. The raised portion of the tube face assures positive film contact with the fiber. Electrostatic focusing offers exceptionally high resolution and eliminates the need for a focus coil around the tube's neck (one less element to mount and adjust). Westinghouse combines this fiber-optic tube with a matching yoke and shield—one precision package ruggedly built to withstand shock and vibration.

Within the Westinghouse Electronic Components and Specialty Products Group, optics meets electronics, solid-state technologies, cryogenics, magnetics and metallurgy. The result is a unique interdisciplinary approach to design and product problems—across an unusually wide range of components, materials and scientific equipment (left and below). Next time, for a broader perspective, bring *us* your problem.

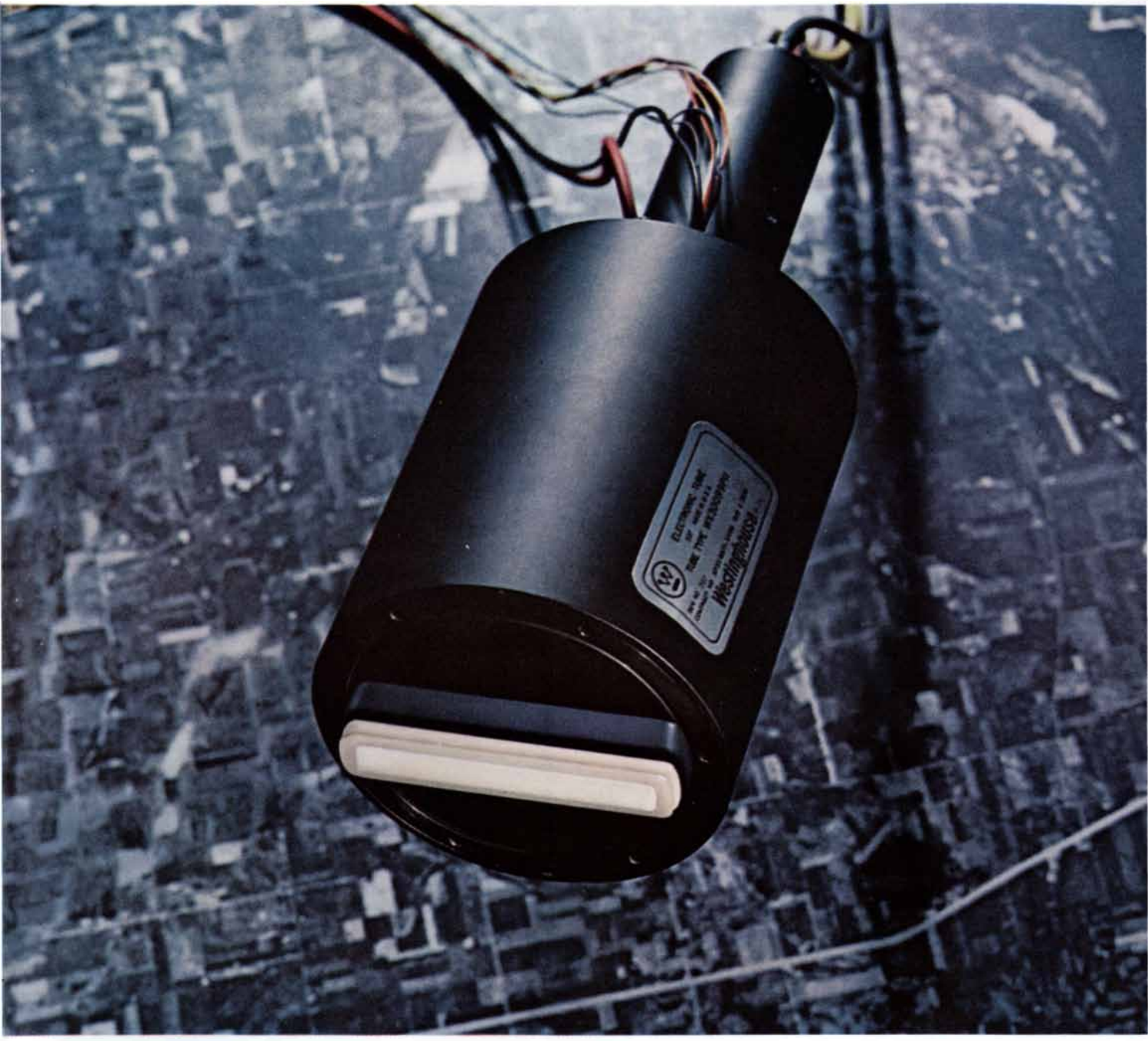




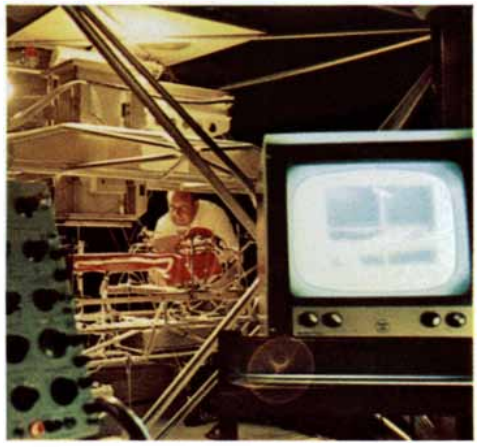
New 32 kw rectifier cartridge occupies 98% less space. Our engineers developed the first high speed diode with a reverse recovery time of 100 nanoseconds. Then this team determined that the characteristics of the diode permitted its use in series networks without the need for conventional external shunting compensation. The result: a revolutionary 32 kw rectifier cartridge only 6⅜″ x ⅞″ that handles up to 16 kv at 2 amperes. Perhaps it could help squeeze some bulk out of *your* high-voltage power supplies. We'll be glad to tell you more.

Only half as much Hipernom® shielding keeps cathode rays on target. Because of its higher initial permeability, half the weight of Hipernom magnetic alloy is needed for the same shielding protection provided by conventional materials. Or the same weight in Hipernom gives *twice* the shielding performance at no increase in cost. Either way, users come out ahead. Westinghouse anneals Hipernom for good deep-drawing, spinning, roll forming and bending; whenever possible, matches the temper to the intended use. Besides shielding, Hipernom is also helping to build better audio transformers, relays, magnetic amplifiers, computer core memories, recording heads, pulse transformers, and magnetometers.

happen when Westinghouse rubs the sciences together



Televex opens a window on the heart at 6 G's. During the acceleration of rocket launch, the blood of astronauts becomes about six times heavier than normal. How this increased weight interferes with circulation is a matter of vital concern to the success of space programs. Westinghouse Televex equipment—a combination of X-ray, closed circuit TV and videotape recording—makes it possible to record an X-ray image of the thorax reacting to this stress under simulated lift-off and reentry conditions. Moreover, any desired area of the image may be brightened to measure passage of contrast media. What is now shedding new light on space problems may soon do the same for heart disease. Write for more facts.



From integrated circuits to magnetic alloys, Westinghouse offers systems-oriented solutions to component problems. You'll find many answers in Westinghouse tubes, semiconductors, integrated molecular circuits, electronic capacitors, instruments and detection equipment, cryogenic systems, transformers, magnetic alloys and magnets, and X-ray systems. For facts and attention to your problem, write S. N. Donahoe, Marketing Manager, Westinghouse Electronic Components and Specialty Products Group, Box 868, Pittsburgh 30, Pennsylvania. J-09003-2

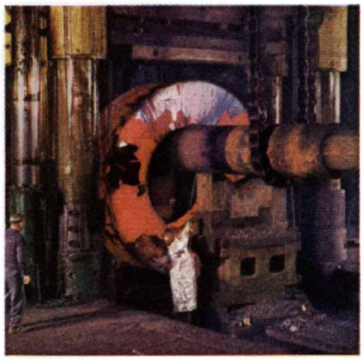
You can be sure if it's Westinghouse

USS Special Report: World's largest stainless steel forgings to contain nuclear energy 3 billion times the power density of the sun

At the National Reactor Testing Station in Idaho, the Atomic Energy Commission is building a tremendous new Advanced Test Reactor (ATR) to test high performance reactor fuels and materials. The fuel core, equivalent to a cube 25 inches on a side, will generate 250,000,000 thermal watts of energy, equal to 336,000 horsepower. This is power density 3 billion times as great as the sun.

ATR's enormous energy will be contained in an immense stainless steel pressure vessel made from eight U. S. Steel forgings. The largest stainless steel forging (above) is 154½ inches in diameter, weighs 39,415 pounds. It is the largest forging of its type ever made. It was made from a forging ingot weighing 233,515 pounds. The huge ingot was forged to a doughnut shape on U. S. Steel's immense 10,000-ton forging press at Homestead Works. The photograph (right) shows a typical reactor flange being mandrel forged at Homestead. After heat treatment and machining, these forgings received an ultrasonic inspection to assure the necessary quality.

U. S. Steel innovation and forging experience have played an important role in our nation's reactor-development program and on many other scientific frontiers. The Nuclear Ship Savannah, world's first nuclear-powered cargo-passenger ship, is propelled by



nine huge USS forged line and propeller shafts. U. S. Steel supplied reactor forgings for the nation's first peacetime atomic energy plant at Shippingport, Pa. The huge, nuclear-powered aircraft carrier USS Enterprise carries U. S. Steel forgings. And in the study of nuclear power—in cyclotrons, synchrotrons, bubble chambers, mass spectrometers, and other high-energy machines—USS forgings have played a vital role for more than two decades.

United States Steel makes a habit of suggesting innovation in the production and use of many steel products. Currently, we are introducing an average of two new or improved products each month. If you believe you could benefit from this brand of thinking, do business with *U. S. Steel . . . where the big idea is innovation.* U. S. Steel, 525 William Penn Place, Pittsburgh, Pa. 15230.

USS TRADEMARK **United States Steel**

Established 1845 SCIENTIFIC AMERICAN November 1964 Volume 211 Number 5

The Origins of New World Civilization

In the Mexican valley of Tehuacán bands of hunters became urban craftsmen in the course of 12,000 years. Their achievement raises some new questions about the evolution of high cultures in general

by Richard S. MacNeish

Perhaps the most significant single occurrence in human history was the development of agriculture and animal husbandry. It has been assumed that this transition from food-gathering to food production took place between 10,000 and 16,000 years ago at a number of places in the highlands of the Middle East. In point of fact the archaeological evidence for the transition, particularly the evidence for domesticated plants, is extremely meager. It is nonetheless widely accepted that the transition represented a "Neolithic Revolution," in which abundant food, a sedentary way of life and an expanding population provided the foundations on which today's high civilizations are built.

The shift from food-gathering to food production did not, however, happen only once. Until comparatively recent times the Old World was for the most part isolated from the New World. Significant contact was confined to a largely one-way migration of culturally primitive Asiatic hunting bands across the Bering Strait. In spite of this almost total absence of traffic between the hemispheres the European adventurers who reached the New World in the 16th century encountered a series of cultures almost as advanced (except in metallurgy and pyrotechnics) and quite as barbarous as their own. Indeed, some of the civilizations from Mexico to Peru possessed a larger variety of domesticated plants than did their European conquerors and had made agricultural advances far beyond those of the Old World.

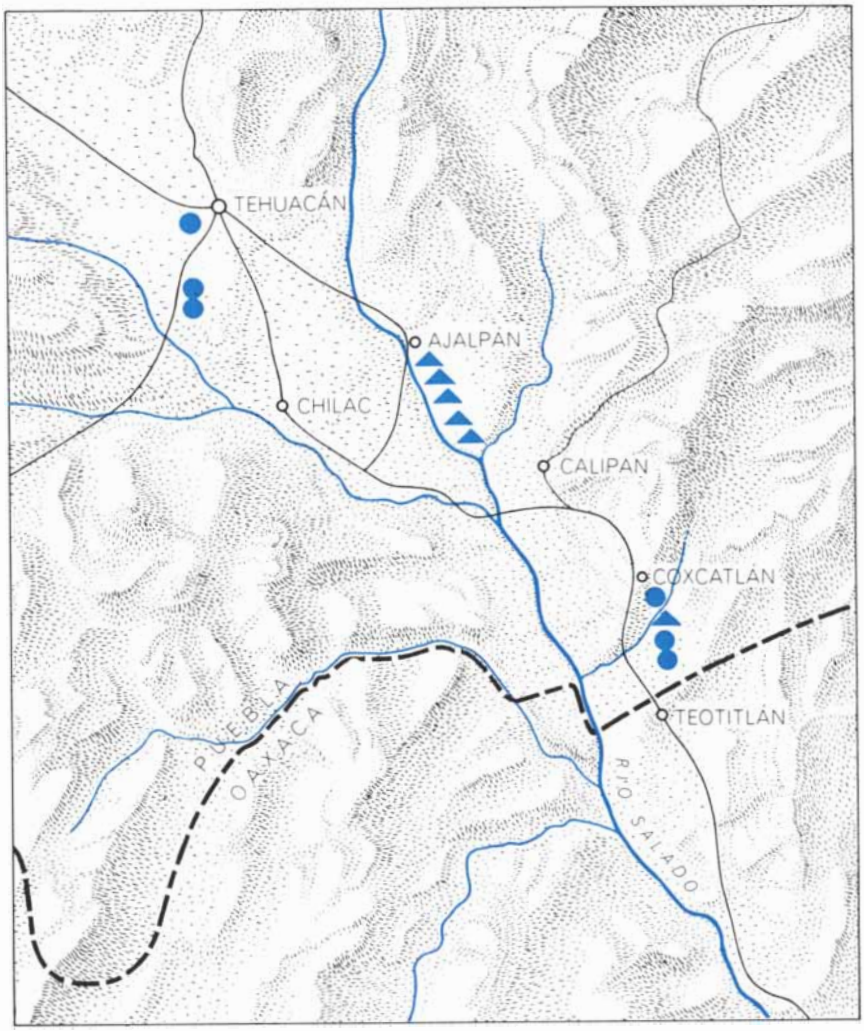
At some time, then, the transition from food-gathering to food production occurred in the New World as it had in the Old. In recent years one of the major problems for New World prehistorians has been to test the hypothesis of a Neolithic Revolution against native archaeological evidence and at the same time to document the American stage of man's initial domestication of plants (which remains almost unknown in both hemispheres).

The differences between the ways in which Old World and New World men achieved independence from the nomadic life of the hunter and gatherer are more striking than the similarities. The principal difference lies in the fact that the peoples of the Old World domesticated many animals and comparatively few plants, whereas in the New World the opposite was the case. The abundant and various herds that gave the peoples of Europe, Africa and Asia meat, milk, wool and beasts of burden were matched in the pre-Columbian New World only by a half-domesticated group of Andean camelloids: the llama, the alpaca and the vicuña. The Andean guinea pig can be considered an inferior equivalent of the Old World's domesticated rabbits and hares; elsewhere in the Americas the turkey was an equally inferior counterpart of the Eastern Hemisphere's many varieties of barnyard fowl. In both the Old World and the New, dogs presumably predated all other domestic animals; in both beekeepers harvested honey and wax. Beyond this the New World list of domestic animals dwindles to nothing. All the cultures of the Americas, high and low alike, depended on their hunters' skill for most of their animal produce: meat and hides, furs and feathers, teeth and claws.

In contrast, the American Indian domesticated a remarkable number of plants. Except for cotton, the "water bottle" gourd, the yam and possibly the coconut (which may have been domesticated independently in each hemisphere), the kinds of crops grown in the Old World and the New were quite different. Both the white and the sweet potato, cultivated in a number of varieties, were unique to the New World. For seasoning, in place of the pepper and mustard of the Old World, the peoples of the New World raised vanilla and at least two kinds of chili. For edible seeds they grew amaranth, chive, panic grass, sunflower, quinoa, apazote, chocolate, the peanut, the common bean and four other kinds of beans: lima, summer, tepary and jack.

In addition to potatoes the Indians cultivated other root crops, including manioc, oca and more than a dozen other South American plants. In place of the Old World melons, the related plants brought to domestication in the New World were the pumpkin, the

TEHUACÁN VALLEY is a narrow desert zone in the mountains on the boundary between the states of Puebla and Oaxaca. It is one of the three areas in southern Mexico selected during the search for early corn on the grounds of dryness (which helps to preserve ancient plant materials) and highland location (corn originally having been a wild highland grass).



SIX CAVES (*dots*) and six open-air sites (*triangles*) have been investigated in detail by the author and his colleagues. Coxcatlán cave (*top dot at right*), where early corn was found in 1960, has the longest habitation record: from well before 7000 B.C. until A.D. 1500.

gourd, the chayote and three or four distinct species of what we call squash. Fruits brought under cultivation in the Americas included the tomato, avocado, pineapple, guava, elderberry and papaya. The pioneering use of tobacco—smoked in pipes, in the form of cigars and even in the form of cane cigarettes, some of which had one end stuffed with fibers to serve as a filter—must also be credited to the Indians.

Above all of these stood Indian corn, *Zea mays*, the only important wild grass in the New World to be transformed into a food grain as the peoples of the Old World had transformed their native grasses into wheat, barley, rye, oats and millet. From Chile to the valley of the St. Lawrence in Canada, one or another of 150 varieties of Indian corn was the staple diet of the pre-Columbian peoples. As a food grain or as fodder, corn remains the most important single crop in the Americas today (and the third largest in the world). Because of its dominant position in New World agriculture, prehistorians have long been confident that if they could find out when and where corn was first domesticated, they might also uncover the origins of New World civilization.

Until little more than a generation ago investigators of this question were beset by twin difficulties. First, research in both Central America and South America had failed to show that any New World high culture significantly predated the Christian era. Second, botanical studies of the varieties of corn and its wild relatives had led more to conflict than to clarity in regard to the domesticated plant's most probable wild predecessor [see "The Mystery of Corn," by Paul C. Mangelsdorf; SCIENTIFIC AMERICAN, July, 1950]. Today, thanks to close cooperation between botanists and archaeologists, both difficulties have almost vanished. At least one starting point for New World agricultural activity has been securely established as being between 5,000 and 9,000 years ago. At the same time botanical analysis of fossil corn ears, grains and pollen, together with plain dirt archaeology, have solved a number of the mysteries concerning the wild origin and domestic evolution of corn. What follows is a review of the recent developments that have done so much to increase our understanding of this key period in New World prehistory.

The interest of botanists in the history of corn is largely practical: they study the genetics of corn in order to produce improved hybrids. After the

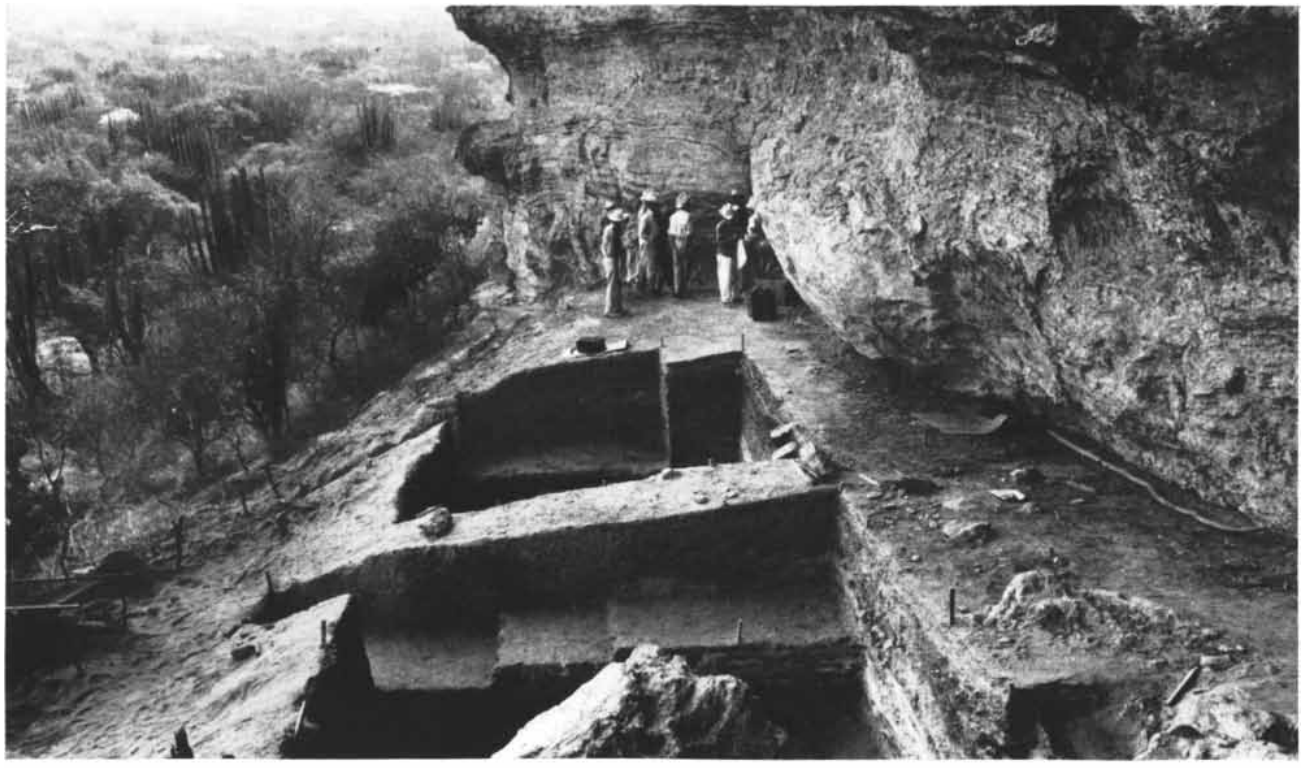
wild ancestors of corn had been sought for nearly a century the search had narrowed to two tassel-bearing New World grasses—teosinte and *Tripsacum*—that had features resembling the domesticated plant. On the basis of crossbreeding experiments and other genetic studies, however, Paul C. Mangelsdorf of Harvard University and other investigators concluded in the 1940's that neither of these plants could be the original ancestor of corn. Instead teosinte appeared to be the product of the accidental crossbreeding of true corn and *Tripsacum*. Mangelsdorf advanced the hypothesis that the wild progenitor of corn was none other than corn itself—probably a popcorn with its kernels encased in pods.

Between 1948 and 1960 a number of discoveries proved Mangelsdorf's contention to be correct. I shall present these discoveries not in their strict chronological order but rather in their order of importance. First in importance, then, were analyses of pollen found in "cores" obtained in 1953 by drilling into the lake beds on which Mexico City is built. At levels that were estimated to be about 80,000 years old—perhaps 50,000 years older than the earliest known human remains in the New World—were found grains of corn pollen. There could be no doubt that the pollen was from wild corn, and thus two aspects of the ancestry of corn were clarified. First, a form of wild corn has been in existence for 80,000 years, so that corn can indeed be descended from itself. Second, wild corn had flourished in the highlands of Mexico. As related archaeological discoveries will make plain, this geographical fact helped to narrow the potential range—from the southwestern U.S. to Peru—within which corn was probably first domesticated.

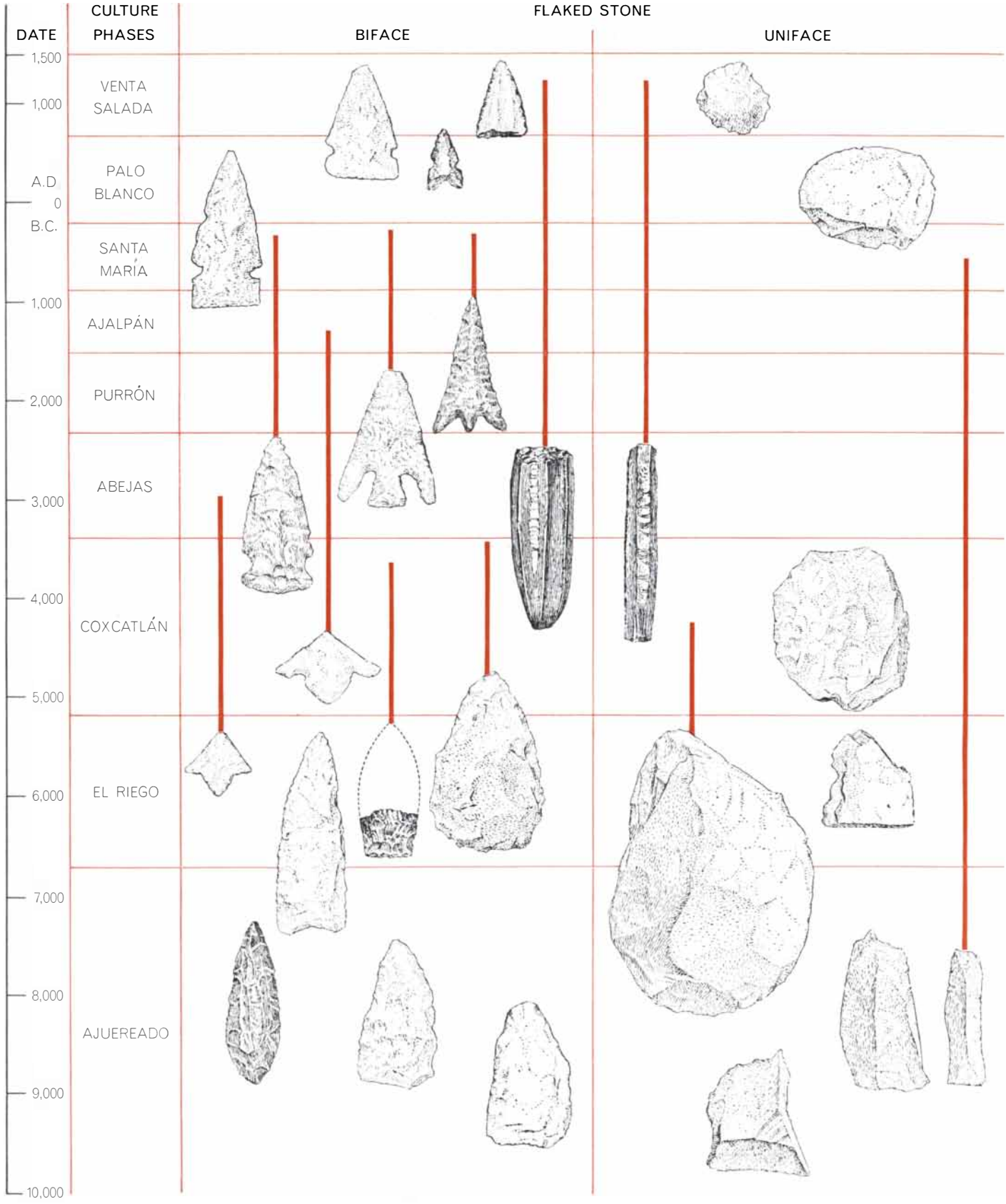
The rest of the key discoveries, involving the close cooperation of archaeologist and botanist, all belong to the realm of paleobotany. In the summer of 1948, for example, Herbert Dick, a graduate student in anthropology who had been working with Mangelsdorf, explored a dry rock-shelter in New Mexico called Bat Cave. Digging down through six feet of accumulated deposits, he and his colleagues found numerous remains of ancient corn, culminating in some tiny corncobs at the lowest level. Carbon-14 dating indicated that these cobs were between 4,000 and 5,000 years old. A few months later, exploring the La Perra cave in the state of Tamaulipas far to the north of Mexico City, I found similar corncobs that proved to be about 4,500 years old. The oldest cobs at both sites came close to fitting the description Mangelsdorf had given of a hypothetical ancestor of the pod-popcorn type. The cobs, however, were clearly those of domesticated corn.

These two finds provided the basis for intensified archaeological efforts to find sites where the first evidences of corn would be even older. The logic was simple: A site old enough should have a level of wild corn remains older than the most ancient domesticated cobs. I continued my explorations near the La Perra cave and excavated a number of other sites in northeastern Mexico. In them I found more samples of ancient corn, but they were no older than those that had already been discovered. Robert Lister, another of Mangelsdorf's coworkers, also found primitive corn in a cave called Swallow's Nest in the Mexican state of Chihuahua, northwest of where I was working, but his finds were no older than mine.

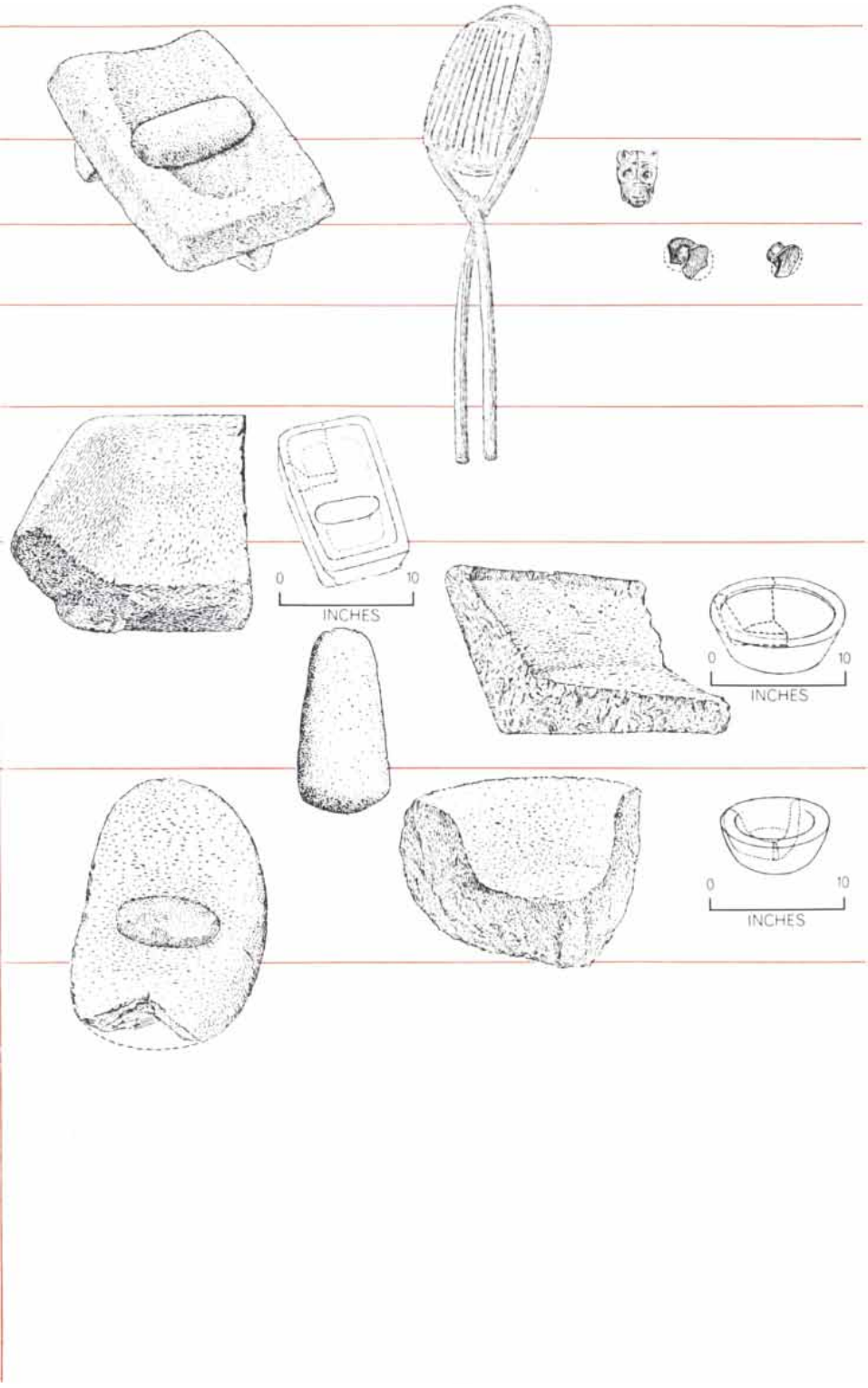
If nothing older than domesticated corn of about 3000 B.C. could be found to the north of Mexico City, it seemed logical to try to the south. In 1958 I went off to look for dry caves and early corn in Guatemala and Honduras. The 1958 diggings produced nothing useful, so in 1959 I moved northward into Chiapas, Mexico's southernmost state. There were no corncobs to be found,



EXCAVATION of Coxcatlán cave required the removal of one-meter squares of cave floor over an area 25 meters long by six meters wide until bedrock was reached at a depth of almost five meters. In this way 28 occupation levels, attributable to seven distinctive culture phases, were discovered. Inhabitants of the three lowest levels lived by hunting and by collecting wild-plant foods.



STONE ARTIFACTS from various Tehuacán sites are arrayed in two major categories: those shaped by chipping and flaking (*left*) and those shaped by grinding and pecking (*right*). Implements that have been chipped on one face only are separated from those that show bifacial workmanship; both groups are reproduced at half their natural size. The ground stone objects are not drawn to a common scale. The horizontal lines define the nine culture phases thus far distinguished in the valley. Vertical lines (*color*) indicate the extent to which the related artifact is known in cultures other than the one in which it is placed. At Tehuacán the evolution of civilization failed to follow the classic pattern established by the Neolithic Revolution in the Old World. For instance, the mortars,



pestles and other ground stone implements that first appear in the El Riego culture phase antedate the first domestication of corn by 1,500 years or more. Not until the Abejas phase, nearly 2,000 years later (marked by sizable obsidian cores and blades and by grinding implements that closely resemble the modern mano and metate), do the earliest village sites appear. More than 1,000 years later, in the Ajalpán phase, earplugs for personal adornment occur. The grooved, withe-bound stone near the top is a pounder for making bark cloth.

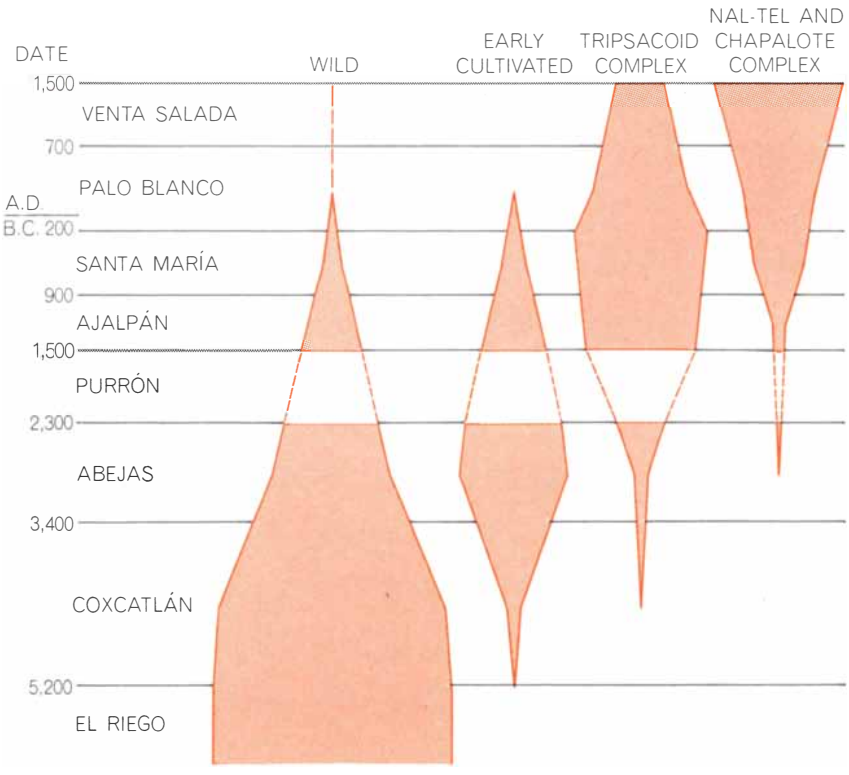
but one cave yielded corn pollen that also dated only to about 3000 B.C. The clues provided by paleobotany now appeared plain. Both to the north of Mexico City and in Mexico City itself (as indicated by the pollen of domesticated corn in the upper levels of the drill cores) the oldest evidence of domesticated corn was no more ancient than about 3000 B.C. Well to the south of Mexico City the oldest date was the same. The area that called for further search should therefore lie south of Mexico City but north of Chiapas.

Two additional considerations enabled me to narrow the area of search even more. First, experience had shown that dry locations offered the best chance of finding preserved specimens of corn. Second, the genetic studies of Mangelsdorf and other investigators indicated that wild corn was originally a highland grass, very possibly able to survive the rigorous climate of highland desert areas. Poring over the map of southern Mexico, I singled out three large highland desert areas: one in the southern part of the state of Oaxaca, one in Guerrero and one in southern Puebla.

Oaxaca yielded nothing of interest, so I moved on to Puebla to explore a dry highland valley known as Tehuacán. My local guides and I scrambled in and out of 38 caves and finally struck pay dirt in the 39th. This was a small rock-shelter near the village of Coxcatlán in the southern part of the valley of Tehuacán. On February 21, 1960, we dug up six corncobs, three of which looked more primitive and older than any I had seen before. Analysis in the carbon-14 laboratory at the University of Michigan confirmed my guess by dating these cobs as 5,600 years old—a good 500 years older than any yet found in the New World.

With this find the time seemed ripe for a large-scale, systematic search. If we had indeed arrived at a place where corn had been domesticated and New World civilization had first stirred, the closing stages of the search would require the special knowledge of many experts. Our primary need was to obtain the sponsorship of an institution interested and experienced in such research, and we were fortunate enough to enlist exactly the right sponsor: the Robert S. Peabody Foundation for Archaeology of Andover, Mass. Funds for the project were supplied by the National Science Foundation and by the agricultural branch of the Rockefeller

EVOLUTION OF CORN at Tehuacán starts (*far left*) with a fragmentary cob of wild corn of 5000 B.C. date. Next (*left to right*) are an early domesticated cob of 4000 B.C., an early hybrid variety of 3000 B.C. and an early variety of modern corn of 1000 B.C. Last (*far right*) is an entirely modern cob of the time of Christ. All are shown four-fifths of natural size.



MAIN VARIETIES OF CORN changed in their relative abundance at Tehuacán between the time of initial cultivation during the Coxcatlán culture phase and the arrival of the conquistadors. Abundant at first, wild corn had become virtually extinct by the start of the Christian era, as had the early cultivated (but not hybridized) varieties. Thereafter the hybrids of the tripsacoid complex (produced by interbreeding wild corn with introduced varieties of corn-*Tripsacum* or corn-teosinte hybrids) were steadily replaced by two still extant types of corn, Nal-Tel and Chapalote. Minor varieties of late corn are not shown.

Foundation in Mexico, which is particularly interested in the origins of corn. The project eventually engaged nearly 50 experts in many specialties, not only archaeology and botany (including experts on many plants other than corn) but also zoology, geography, geology, ecology, genetics, ethnology and other disciplines.

The Coxcatlán cave, where the intensive new hunt had begun, turned out to be our richest dig. Working downward, we found that the cave had 28 separate occupation levels, the earliest of which may date to about 10,000 B.C. This remarkably long sequence has one major interruption: the period between 2300 B.C. and 900 B.C. The time from 900 B.C. to A.D. 1500, however, is represented by seven occupation levels. In combination with our findings in the Purrón cave, which contains 25 floors that date from about 7000 B.C. to 500 B.C., we have an almost continuous record (the longest interruption is less than 500 years) of nearly 12,000 years of prehistory. This is by far the longest record for any New World area.

All together we undertook major excavations at 12 sites in the valley of Tehuacán [*see bottom illustration on page 30*]. Of these only five caves—Coxcatlán, Purrón, San Marcos, Tecoral and El Riego East—contained remains of ancient corn. But these and the other stratified sites gave us a wealth of additional information about the people who inhabited the valley over a span of 12,000 years. In four seasons of digging, from 1961 through 1964, we reaped a vast archaeological harvest. This includes nearly a million individual remains of human activity, more than 1,000 animal bones (including those of extinct antelopes and horses), 80,000 individual wild-plant remains and some 25,000 specimens of corn. The artifacts arrange themselves into significant sequences of stone tools, textiles and pottery. They provide an almost continuous picture of the rise of civilization in the valley of Tehuacán. From the valley's geology, from the shells of its land snails, from the pollen and other remains of its plants and from a variety of other relics our group of specialists has traced the changes in climate, physical environment and plant and animal life that took place during the 12,000 years. They have even been able to tell (from the kinds of plant remains in various occupation levels) at what seasons of the year many of the floors in the caves were occupied.

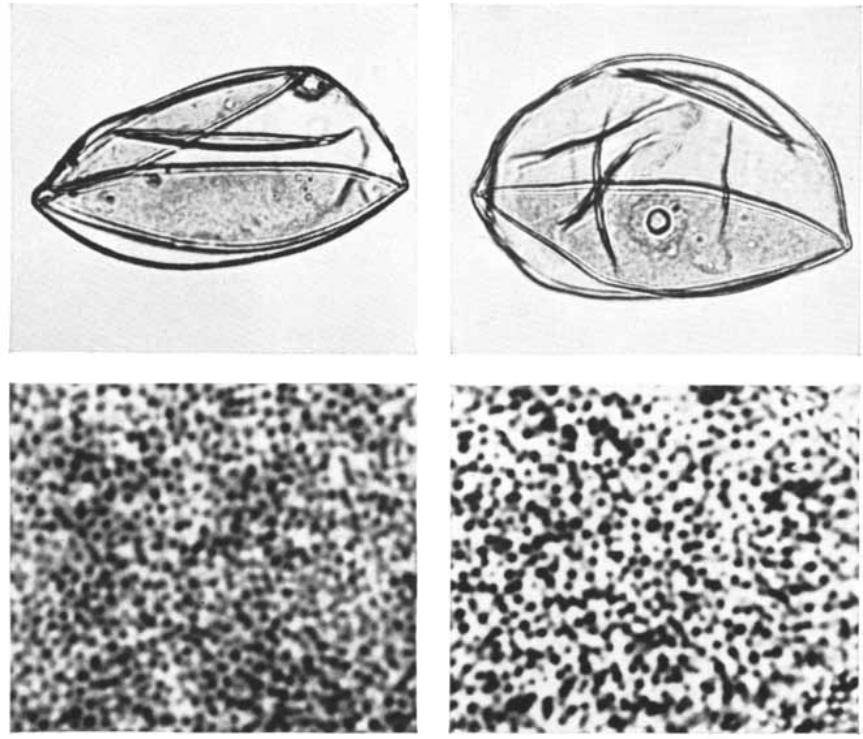
Outstanding among our many finds was a collection of minuscule corncobs

that we tenderly extracted from the lowest of five occupation levels at the San Marcos cave. They were only about 20 millimeters long, no bigger than the filter tip of a cigarette [*see top illustration on opposite page*], but under a magnifying lens one could see that they were indeed miniature ears of corn, with sockets that had once contained kernels enclosed in pods. These cobs proved to be some 7,000 years old. Mangelsdorf is convinced that this must be wild corn—the original parent from which modern corn is descended.

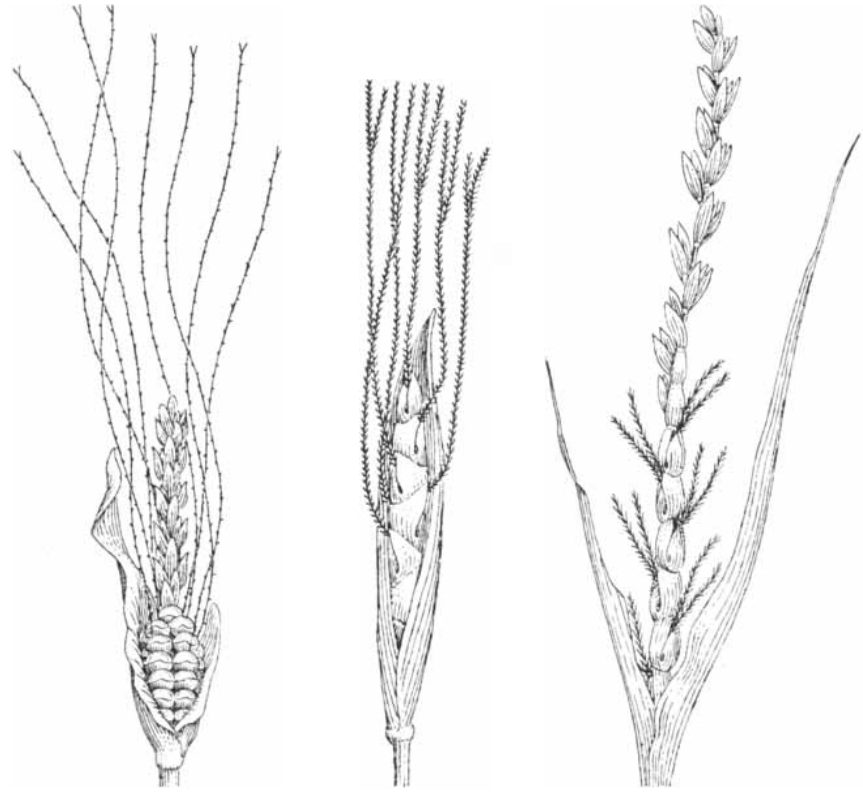
Cultivated corn, of course, cannot survive without man's intervention; the dozens of seeds on each cob are enveloped by a tough, thick husk that prevents them from scattering. Mangelsdorf has concluded that corn's wild progenitor probably consisted of a single seed spike on the stalk, with a few pod-covered ovules arrayed on the spike and a pollen-bearing tassel attached to the spike's end [*see bottom illustration at right*]. The most primitive cobs we unearthed in the valley of Tehuacán fulfilled these specifications. Each had the stump of a tassel at the end, each had borne kernels of the pod-popcorn type and each had been covered with only a light husk consisting of two leaves. These characteristics would have allowed the plant to disperse its seeds at maturity; the pods would then have protected the seeds until conditions were appropriate for germination.

The people of the valley of Tehuacán lived for thousands of years as collectors of wild vegetable and animal foods before they made their first timid efforts as agriculturists. It would therefore be foolhardy to suggest that the inhabitants of this arid highland pocket of Mexico were the first or the only people in the Western Hemisphere to bring wild corn under cultivation. On the contrary, the New World's invention of agriculture will probably prove to be geographically fragmented. What can be said for the people of Tehuacán is that they are the first whose evolution from primitive food collectors to civilized agriculturists has been traced in detail. As yet we have no such complete story either for the Old World or for other parts of the New World. This story is as follows.

From a hazy beginning some 12,000 years ago until about 7000 B.C. the people of Tehuacán were few in number. They wandered the valley from season to season in search of jackrabbits, rats, birds, turtles and other small animals, as well as such plant foods as be-



ANTIQUITY OF CORN in the New World was conclusively demonstrated when grains of pollen were found in drilling cores taken from Mexico City lake-bottom strata estimated to be 80,000 years old. Top two photographs (*magnification 435 diameters*) compare the ancient corn pollen (*left*) with modern pollen (*right*). Lower photographs (*magnification 4,500 diameters*) reveal similar ancient (*left*) and modern (*right*) pollen surface markings. The analysis and photographs are the work of Elso S. Barghoorn of Harvard University.



THREE NEW WORLD GRASSES are involved in the history of domesticated corn. Wild corn (*reconstruction at left*) was a pod-pop variety in which the male efflorescence grew from the end of the cob. Teosinte (*center*) and *Tripsacum* (*right*) are corn relatives that readily hybridized with wild and cultivated corn. Modern corn came from such crosses.

came available at different times of the year. Only occasionally did they manage to kill one of the now extinct species of horses and antelopes whose bones mark the lowest cave strata. These people used only a few simple implements of flaked stone: leaf-shaped projectile points, scrapers and engraving tools. We have named this earliest culture period the Ajuereado phase [*see illustration on pages 32 and 33*].

Around 6700 B.C. this simple pattern changed and a new phase—which we have named the El Riego culture from the cave where its first evidences appear—came into being. From then until about 5000 B.C. the people shifted from being predominantly trappers and hunters to being predominantly collectors of plant foods. Most of the plants they collected were wild, but they had domesticated squashes (starting with the species *Cucurbita mixta*) and avocados, and they also ate wild varieties of beans, amaranth and chili peppers. Among the flaked-stone implements, choppers appear. Entirely new kinds of stone tools—grinders, mortars, pestles and pounders of polished stone—are found in large numbers. During the growing season some families evidently gathered in temporary settlements, but these groups broke up into one-family bands during the leaner periods of the year. A number of burials dating from this culture phase hint at the possibility of part-time priests or witch doctors who directed the ceremonies involving the dead. The El Riego culture, however, had no corn.

By about 5000 B.C. a new phase, which we call the Coxcatlán culture, had evolved. In this period only 10 percent of the valley's foodstuffs came from domestication rather than from collecting, hunting or trapping, but the list of domesticated plants is long. It includes corn, the water-bottle gourd, two species of squash, the amaranth, black and white zapotes, the tepary bean (*Phaseolus acutifolius*), the jack bean (*Canavalia ensiformis*), probably the common bean (*Phaseolus vulgaris*) and chili peppers.

Coxcatlán projectile points tend to be smaller than their predecessors; scrapers and choppers, however, remain much the same. The polished stone implements include forerunners of the classic New World roller-and-stone device for grinding grain: the mano and metate. There was evidently enough surplus energy among the people to allow the laborious hollowing out of stone water jugs and bowls.

It was in the phase following the Coxcatlán that the people of Tehuacán made the fundamental shift. By about 3400 B.C. the food provided by agriculture rose to about 30 percent of the total, domesticated animals (starting with the dog) made their appearance, and the people formed their first fixed settlements—small pit-house villages. By this stage (which we call the Abejas culture) they lived at a subsistence level that can be regarded as a foundation for the beginning of civilization. In about 2300 B.C. this gave way to the Purrón culture, marked by the cultivation of more hybridized types of corn and the manufacture of pottery.

Thereafter the pace of civilization in the valley speeded up greatly. The descendants of the Purrón people developed a culture (called Ajalpán) that from about 1500 B.C. on involved a more complex village life, refinements of pottery and more elaborate ceremonialism, including the development of a figurine cult, perhaps representing family gods. This culture led in turn to an even more sophisticated one (which we call Santa María) that started about 850 B.C. Taking advantage of the valley's streams, the Santa María peoples of Tehuacán began to grow their hybrid corn in irrigated fields. Our surveys indicate a sharp rise in population. Temple mounds were built, and artifacts show signs of numerous contacts with cultures outside the valley. The Tehuacán culture in this period seems to have been strongly influenced by that of the Olmec people who lived to the southeast along the coast of Veracruz.

By about 200 B.C. the outside influence on Tehuacán affairs shifted from that of the Olmec of the east coast to that of Monte Alban to the south and west. The valley now had large irrigation projects and substantial hilltop ceremonial centers surrounded by villages. In this Palo Blanco phase some of the population proceeded to full-time specialization in various occupations, including the development of a salt industry. New domesticated food products appeared—the turkey, the tomato, the peanut and the guava. In the next period—Venta Salada, starting about A.D. 700—Monte Alban influences gave way to the influence of the Mixtecs. This period saw the rise of true

COXCATLÁN CAVE BURIAL, dating to about A.D. 100, contained the extended body of an adolescent American Indian, wrapped in a pair of cotton blankets with brightly colored stripes. This bundle in turn rested on sticks and the whole was wrapped in bark cloth.

cities in the valley, of an agricultural system that provided some 85 percent of the total food supply, of trade and commerce, a standing army, large-scale irrigation projects and a complex religion. Finally, just before the Spanish Conquest, the Aztecs took over from the Mixtecs.

Our archaeological study of the valley of Tehuacán, carried forward in collaboration with workers in so many other disciplines, has been gratifyingly productive. Not only have we documented one example of the origin of domesticated corn but also comparative studies of other domesticated plants have indicated that there were multiple centers of plant domestication in the Americas. At least for the moment we have at Tehuacán not only evidence of the earliest village life in the New World but also the first (and worst) pottery in Mexico and a fairly large sample of skeletons of some of the earliest Indians yet known.

Even more important is the fact that we at last have one New World example of the development of a culture from savagery to civilization. Preliminary analysis of the Tehuacán materials indicate that the traditional hypothesis about the evolution of high cultures may have to be reexamined and modified. In southern Mexico many of the characteristic elements of the Old World's Neolithic Revolution fail to appear suddenly in the form of a new culture complex or a revolutionized way of life. For example, tools of ground (rather than chipped) stone first occur at Tehuacán about 6700 B.C., and plant domestication begins at least by 5000 B.C. The other classic elements of the Old World Neolithic, however, are slow to appear. Villages are not found until around 3000 B.C., nor pottery until around 2300 B.C., and a sudden increase in population is delayed until 500 B.C. Reviewing this record, I think more in terms of Neolithic "evolution" than "revolution."

Our preliminary researches at Tehuacán suggest rich fields for further exploration. There is need not only for detailed investigations of the domestication and development of other New World food plants but also for attempts to obtain similar data for the Old World. Then—perhaps most challenging of all—there is the need for comparative studies of the similarities and differences between evolving cultures in the Old World and the New to determine the hows and whys of the rise of civilization itself.

SOPHISTICATED FIGURINE of painted pottery is one example of the artistic capacity of Tehuacán village craftsmen. This specimen, 2,900 years old, shows Olmec influences.

EXPLODING GALAXIES

Evidence of a titanic explosion in the nucleus of a nearby radio galaxy suggests that such events may be responsible for a large part of the cosmic radiation striking the earth

by Allan R. Sandage

Of the major unsolved problems in astrophysics, none has received more attention over the past 50 years than the origin of cosmic radiation. Since the discovery of cosmic rays in 1911 by Victor F. Hess of Austria a number of theories have been put forward to explain where and how these ultrahigh-energy charged particles (mostly protons, with a small admixture of heavier atomic nuclei) could be accelerated to their enormous velocities. The discovery of supernovae in the decade after 1925 began a train of speculation that attributed cosmic rays to exploding stars in our galaxy. An alternate theory, proposed by the late Enrico Fermi, held that low-energy particles emitted by stars like the sun are gradually accelerated to cosmic ray velocities by repeated encounters with local magnetic fields within the galaxy.

During the past 10 years many astrophysicists have favored still another explanation, which places the source of at least part of the cosmic radiation in events occurring outside our galaxy. There has been strong circumstantial evidence that titanic explosions are taking place in the central regions of certain galaxies—perhaps including our own! The energy released in these explosions could account for the highest observed cosmic ray energies and for at least part of the low-energy flux. This hypothesis has recently received strong support from observations of a neighboring galaxy that indicate that the galaxy was the scene of such an explosion some 1.5 million years ago.

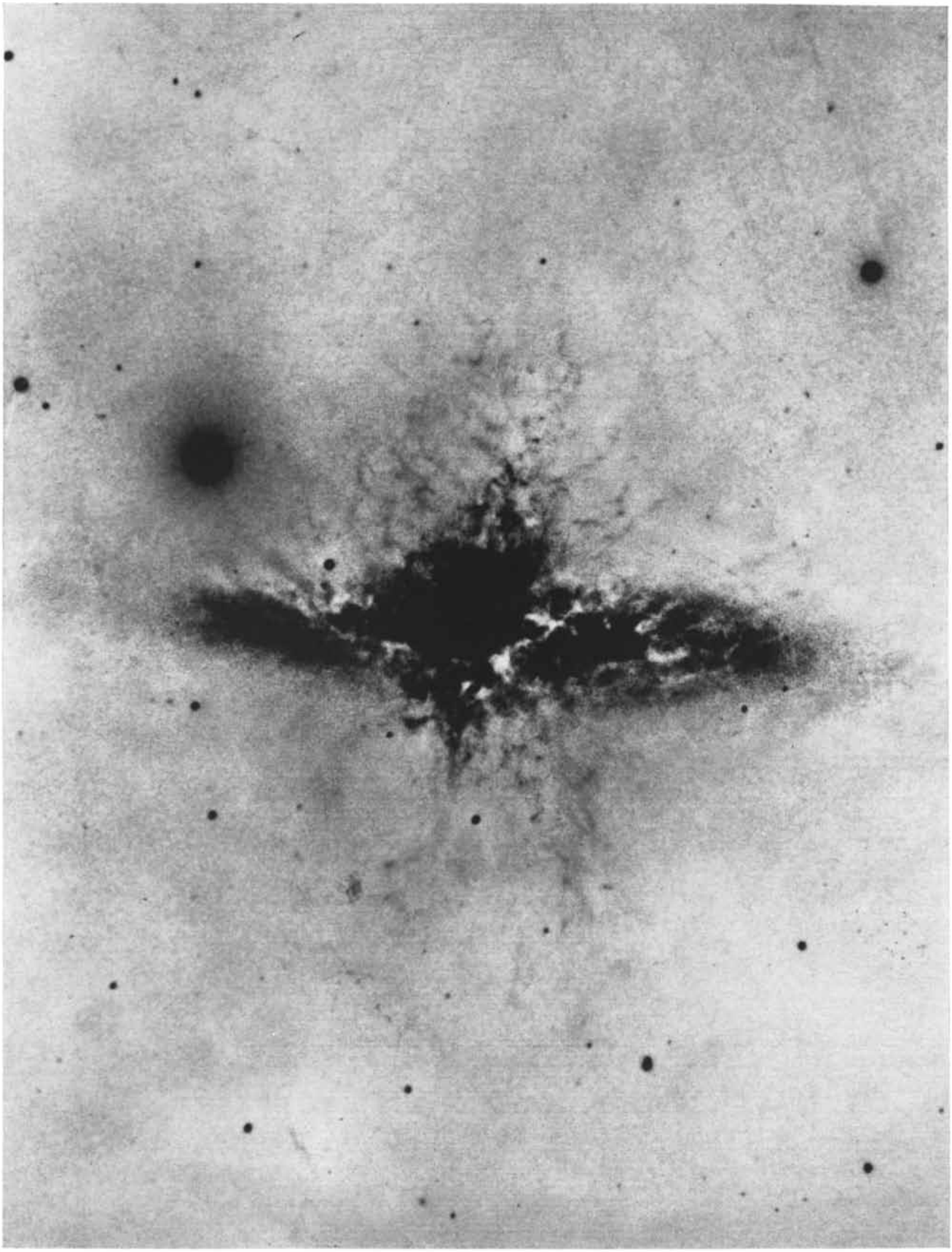
The evidence for the view that cosmic rays originate in galactic explosions has come largely from radio astronomy. In 1946 the first discrete source of radio waves outside our solar system was discovered. It appeared on radio-contour maps as an intense spot in the constellation of Cygnus and was accordingly designated Cygnus A. By 1948 radio astronomers in Australia and Britain had detected additional discrete sources in the constellations of Taurus, Cassiopeia, Centaurus and Hercules. At last count more than 3,000 discrete radio sources had been mapped, and the number will probably pass 100,000 when comprehensive surveys now in progress are completed.

In 1951 Rudolph Minkowski and Walter Baade of the Mount Wilson and Palomar Observatories made the first identification of a discrete radio source with an optically visible object. Their photographs, made with the 200-inch telescope on Palomar Mountain, showed that Cygnus A coincided with the position of a galaxy now estimated to be some 700 million light-years away. Shortly thereafter the radio sources Virgo A and Centaurus A were found to coincide with the giant galaxies designated 4486 and 5128 in the New General Catalogue (NGC). More than 100 of the discrete radio sources have since been identified with visible galaxies, and it is likely that most of the other sources are associated with radio galaxies either too distant to be seen or very near the limit of the 200-inch telescope [see "Radio Galaxies," by D. S. Heeschen; SCIENTIFIC AMERICAN, March, 1962].

The mechanism by which electromagnetic radiation in the radio region of the spectrum is generated by radio galaxies has been the subject of much conjecture. The most plausible explanation was originally suggested in 1950 by Hannes Alfvén and N. Herlofson of Sweden and subsequently developed by the Soviet astrophysicist I. S. Shklovsky. According to this model, radio waves are generated by the interaction of relativistic electrons (that is, electrons moving with velocities close to the speed of light) and a magnetic field. As an electron gyrates around a line of force in a magnetic field, it accelerates and consequently emits energy in the form of electromagnetic radiation. This radiation, which can be generated by any charged particle, is sometimes called synchrotron radiation, since it is identical with the radiation produced in the man-made particle accelerators known as synchrotrons.

The wavelength of any synchrotron radiation depends on the energy of the gyrating particles and on the strength of the magnetic field. Radio waves are produced when the electron energies lie between one billion and 25 billion electron volts (bev) and the magnetic field has a strength of about a millionth of a gauss. These specifications are amply met by radio galaxies. In fact, high as these electron energies are, they may represent only the low-energy "tail" of the actual energy-distribution curve of radio galaxies. For example, M 87 is an intense radio galaxy in which the electron energies appear to be at least 10,000 bev, far higher than the energy of the particles produced in any man-made accelerator.

What does all this have to do with cosmic rays? It seems likely that at least some of the charged particles involved in the production of synchrotron radio waves must eventually escape the magnetic fields of the radio galaxies and fly off into intergalactic space. These particles, together with particles generated by similar explosions in our own galaxy, could account for the flux of primary cosmic radiation that impinges on the earth. (The secondary radiation at the surface of the earth is of course the result of the disruption of atoms in the

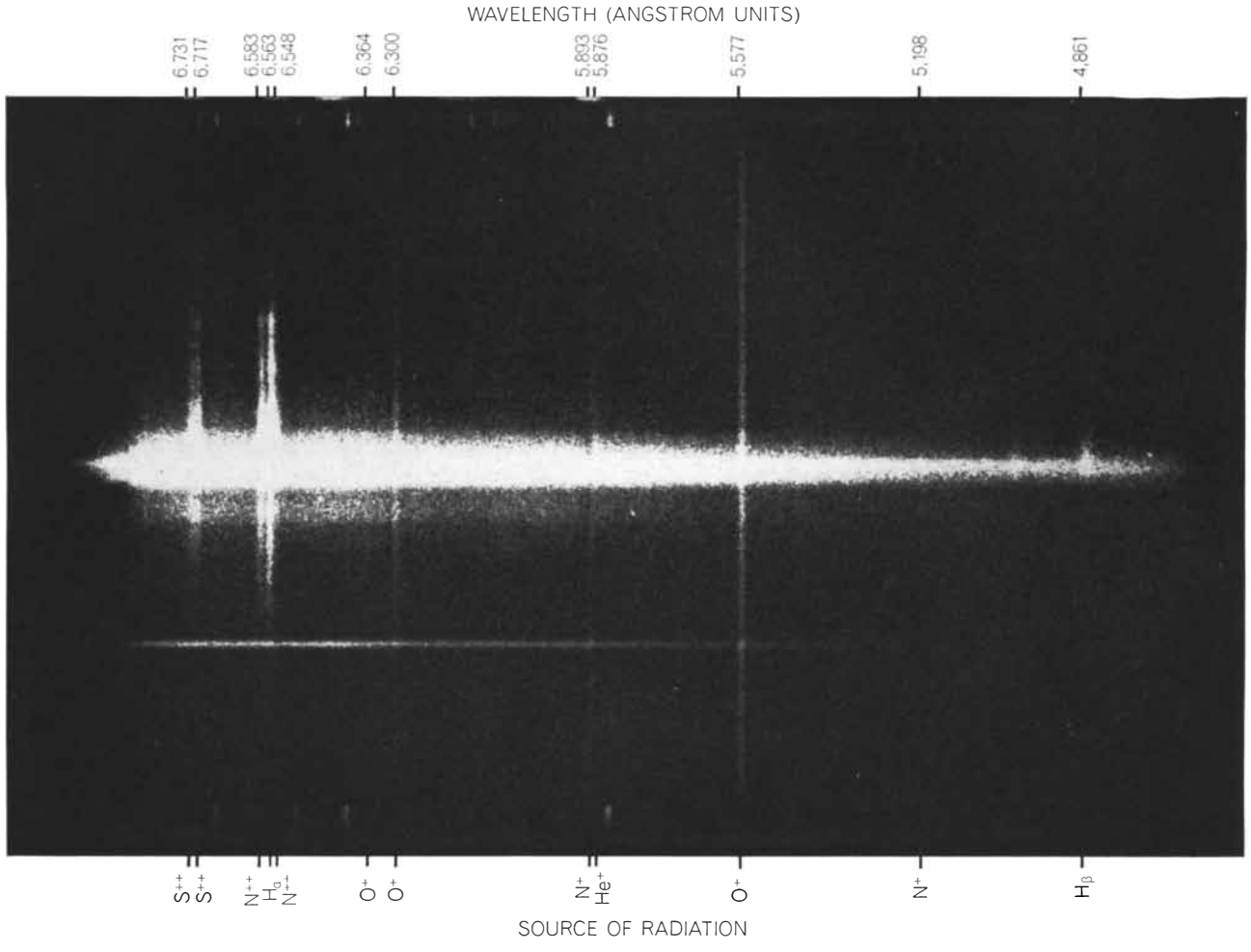


PHOTOGRAPH OF M 82, a nearby radio-emitting galaxy, was made in red light by the author with the 200-inch telescope on Palomar Mountain. This photograph revealed for the first time the spectacular array of hydrogen filaments that extend more than 14,000 light-years above and below the galactic disk of M 82. An explosion at the center of the galaxy presumably ejected the filaments some 1.5 million years ago. Enlargement of this photograph is the same as that in color photograph of M 82 that appears on the cover of this issue. Most of the astronomical photographs in this article are printed as negatives in order to accentuate fine details.

earth's atmosphere by the primary radiation.) Considering the density of radio galaxies in space, their estimated lifetimes and their total output of energy (and also taking into account the production of particles in our own galaxy), this explanation comes close to predicting both the intensity of the observed cosmic radiation and the velocity of its most energetic particles. If we attribute both the discrete radio sources and the cosmic ray flux to synchrotron radiation, we can assume that the immediate source of energy for the synchrotron radiation must be galactic explosions of prodigious magnitude.

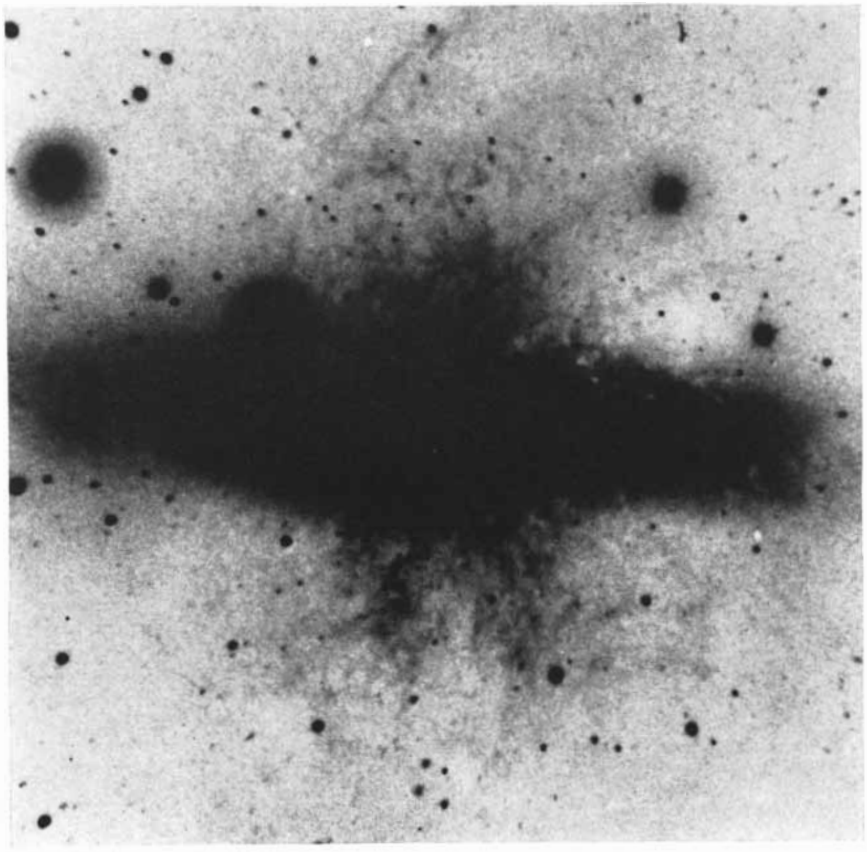
As the exploding-galaxy hypothesis gained gradual acceptance during the 1950's it provided a working model for interpreting new data. For example, in 1953 R. C. Jennison and M. K. Das Gupta of the Jodrell Bank radio observatory of the University of Manchester discovered that Cygnus A was *not* a single discrete radio source but rather could be resolved into two separate radio-emitting regions located on opposite sides of the visible galaxy at distances of about 100,000 light-years. Subsequent studies by radio astronomers at Jodrell Bank and at the California Institute of Technology showed that this phenomenon, sometimes called radio doubling, is probably the rule rather than the exception among radio galaxies. Presumably the twin radio regions represent two jets of high-energy particles ejected by the parent galaxy in an explosion millions of years ago. Conserving angular momentum, the jets would move in opposite directions from the center of the galaxy. They would carry part of the galaxy's magnetic field with them, or perhaps encounter another field in intergalactic space. Synchrotron radiation would be produced all along the jets, but it would be most concentrated at the ends, where the lines of force in the magnetic field would be most tightly compressed; in effect, two discrete spots of intense radio emission would be observed.

In spite of the persuasive evidence of the radio observations, the exploding-galaxy hypothesis still lacked optical support. Then, in 1961, a discovery was made that was to lead eventually to the necessary confirmation. Early in that year C. R. Lynds, working at the National Radio Astronomy Observatory in Green Bank, W.Va., was surveying a group of visible galaxies centered on



SPECTROGRAM OF M 82 was obtained by C. R. Lynds at the Lick Observatory by placing the slit of a spectroscope attached to the 120-inch telescope along the axis of the filamentary structure, perpendicular to the plane of the galaxy. The broad streak across the center is the continuous spectrum of the galactic nucleus. The vertical lines are characteristic emission lines produced by the recombination of ionized atoms in the filaments; the wavelengths of several of these lines are given at top. The letters at bottom designate the elements responsible for the emission lines; the superscript plus signs after some of the letters signify whether that element is singly or doubly ionized. Two characteristic emission lines of hydrogen are indicated by the subscript Greek letters. All the emission lines are inclined slightly with respect to the laboratory comparison lines (*short lines along top and bottom of plate*). This indicated that the filaments on one side of galactic disk are approaching the earth, whereas those on the other side are receding.

the giant spiral galaxy M 81 in an attempt to locate a weak radio source designated 3C 231 in the third Cambridge catalogue of radio sources. This source had previously been identified with M 81 itself, but Lynds's more accurate measurements showed that it actually coincided with the peculiar galaxy M 82, a smaller neighbor of M 81. Older photographs of M 82, made as long ago as 1910 with the 60-inch telescope on Mount Wilson, showed that this galaxy could not be resolved into individual stars, although at its distance normal stars should have been visible within the galaxy. The old plates showed extensive dust lanes across the spindle-shaped image of the galaxy, with a faint filamentary structure extending above and below the galactic disk. In 1949, soon after the 200-inch telescope went into operation on Palomar Mountain, M 82 was rephotographed; the newer photographs showed the filamentary structures more clearly, but optical observations were not pushed further until Lynds's discovery in 1961 that the galaxy was a discrete radio source.

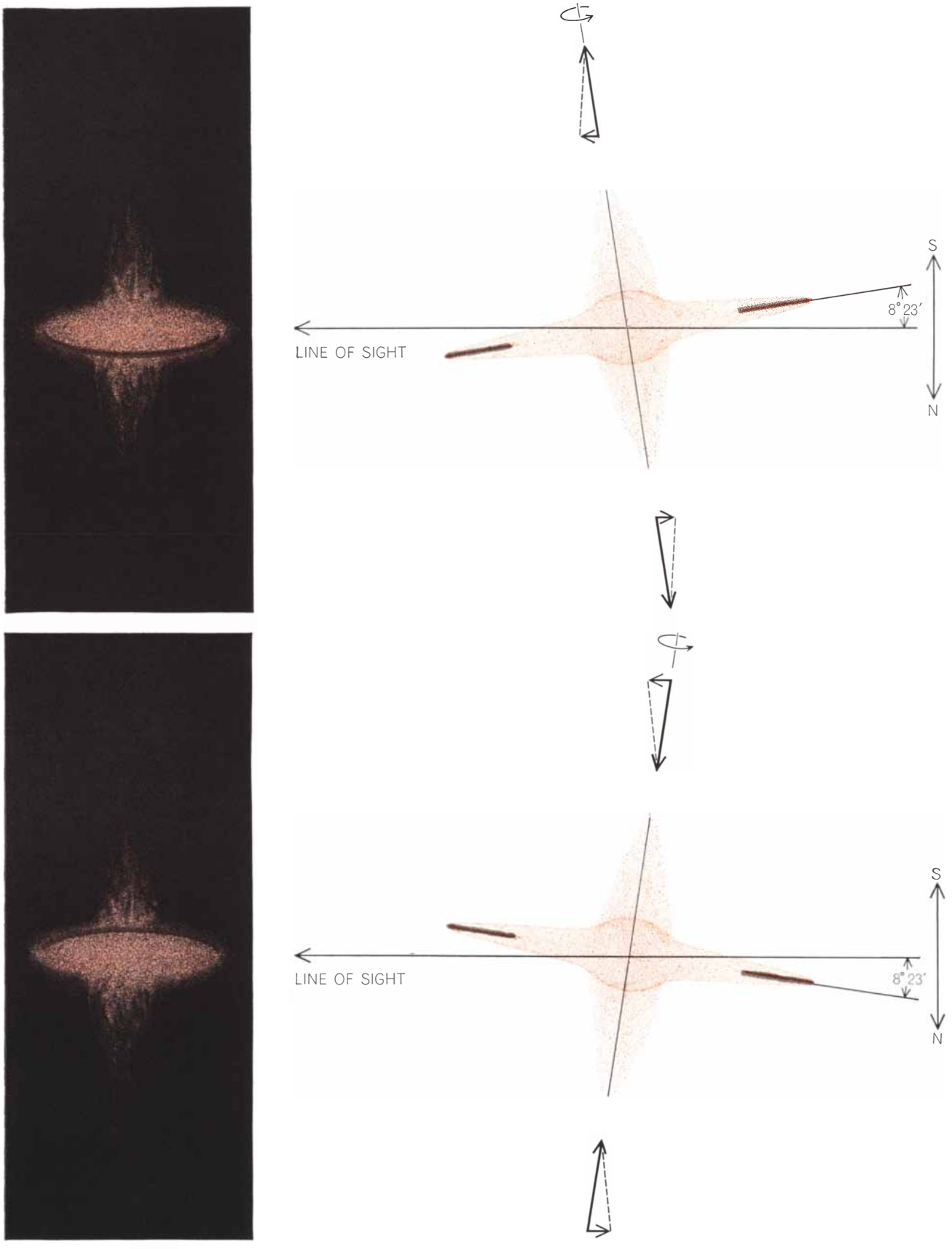


COMPOSITE PRINT OF M 82 was made by William C. Miller of the Mount Wilson and Palomar Observatories by superposing three photographs made in blue light by the author with the 200-inch telescope. The continuous radiation emitted by outer fringe of blue filaments provides strong evidence that the hydrogen gas in the filaments was originally ionized by synchrotron radiation, which in turn was generated by relativistic electrons (that is, electrons moving with speeds close to that of light) produced in explosion of galactic nucleus.

Stimulated by Lynds's findings, I decided to make a new series of photographs of M 82 in March, 1962, using the 200-inch telescope. A special interference filter that admitted only red light with a wavelength of 6,563 angstrom units was employed in order to detect any prominent hydrogen structures that would otherwise go unnoticed. (The spectral line at 6,563 angstroms, known to spectroscopists as the hydrogen-alpha line, is characteristic of radiation produced by the recombination of ionized hydrogen atoms.) To my surprise the new plates showed M 82 in an entirely new aspect. What had appeared on the old plates as inconspicuous filamentary wisps now appeared as vast and intricate hydrogen structures, extending some 14,000 light-years above and below the plane of the galaxy [*see illustration on page 39*].

Meanwhile Lynds had undertaken an independent spectral analysis of M 82, using the 120-inch telescope at the Lick Observatory. He found that when the slit of the spectroscope was placed along the axis of the filamentary structure, perpendicular to the plane of the galaxy, characteristic emission lines of hydrogen, sulfur and nitrogen appeared in the spectra in great strength. Close examination of the plates revealed that the emission lines were inclined slightly with respect to the laboratory comparison lines that had been superposed

POSITIVE PRINT of spiral galaxy NGC 4216 provides an unambiguous example of the rule that for galaxies seen almost edge on, dark dust lanes identify the edge closer to earth.



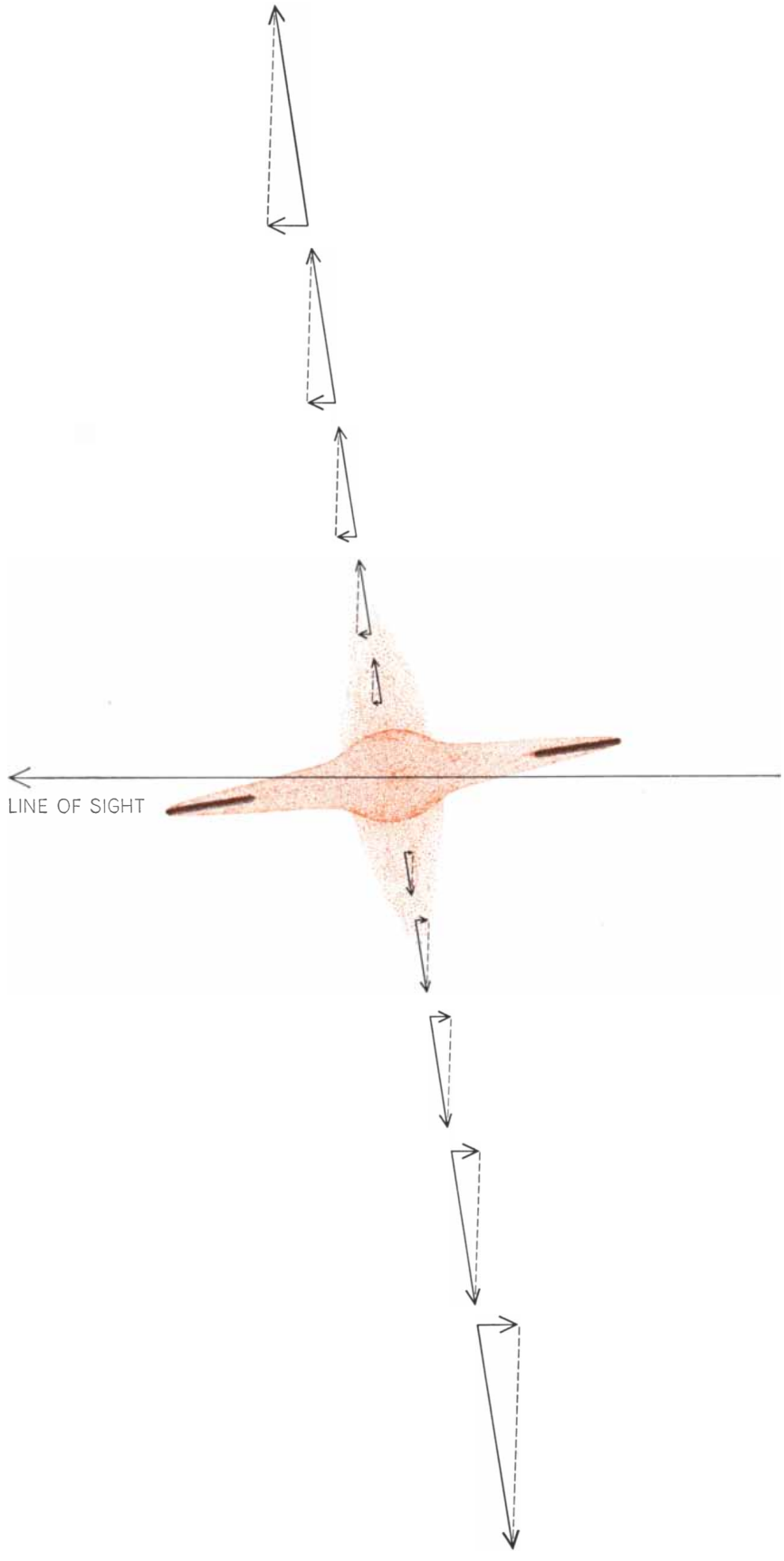
ORIENTATION OF M 82 along the line of sight had to be ascertained in order to decide whether the galaxy was expanding or collapsing. The two possible interpretations of the spectral data are shown here. In each case the picture at left shows the galaxy as it would be seen from the earth; the pictures at right are hypothetical side views of the two possible orientations. If the north edge were closer to the earth (*top*), the spectral data would indicate that the galaxy was expanding. If the south edge were closer (*bottom*), the galaxy would be collapsing. The dark dust lanes that actually appear along the north edge of the galaxy indicate that that side is closer and hence that the galaxy must be expanding. Tilt of galaxy along the line of sight was calculated independently.

on the plates [*see illustration on page 40*]. This tilting of the spectral lines could only mean that the filamentary structure on one side of the galactic disk was approaching the earth, whereas the structure on the other side was receding. Mass motion on so vast a scale had never before been observed perpendicular to a galactic disk.

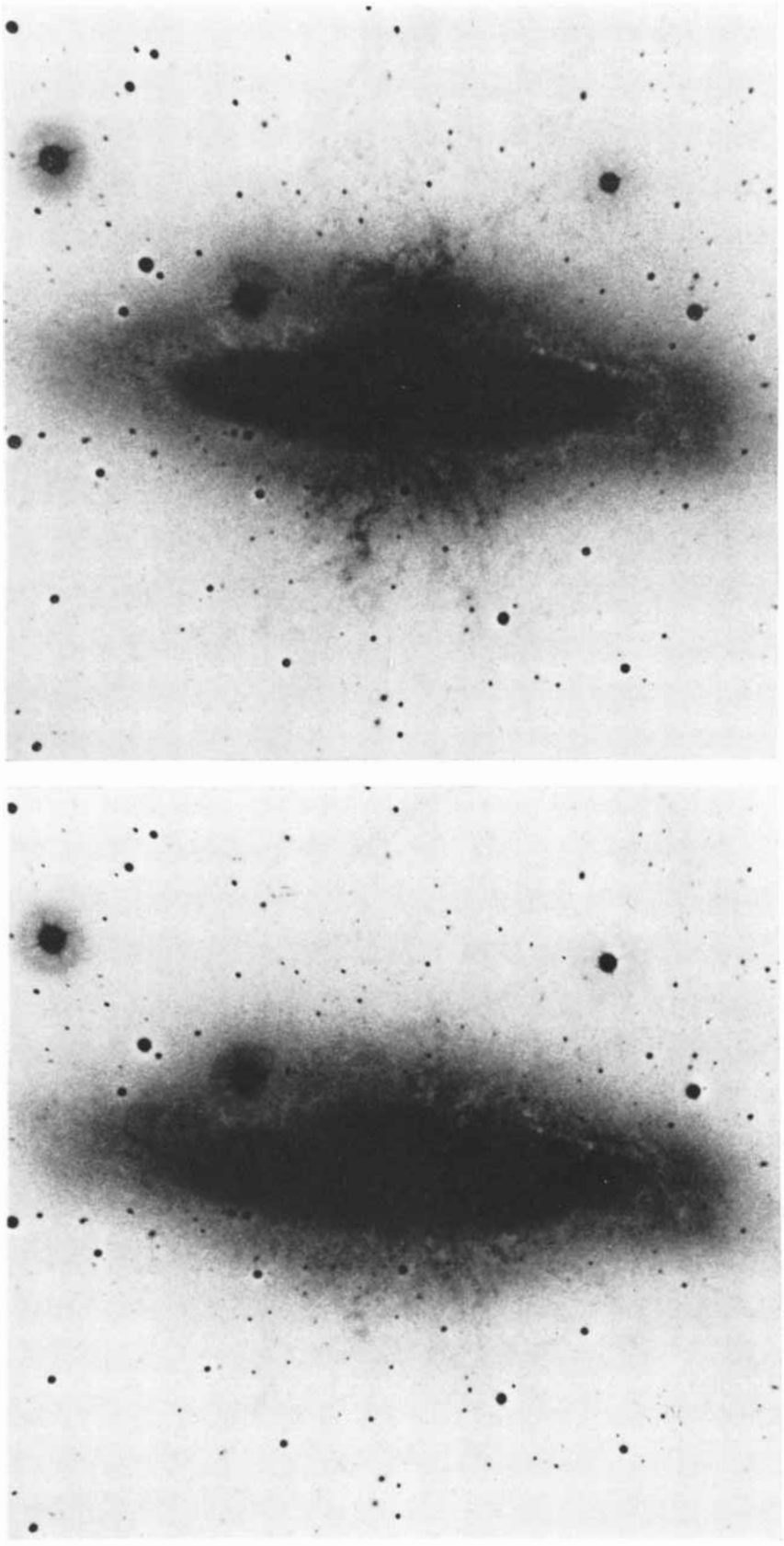
At first the tilting of the spectral lines could be interpreted as evidence for either an explosion or an implosion. The data merely showed that the filaments on the south side of the galactic disk were approaching the earth and that the filaments on the north side were receding. If the north edge of the galactic disk were nearer the earth, the spectral tilting would indicate that the galaxy was in the process of expanding. If the south edge were nearer, the galaxy would be collapsing.

To decide whether M 82 was exploding or imploding, we adopted a simple criterion established in the 1920's by V. M. Slipher of the Lowell Observatory in Flagstaff, Ariz. Slipher had pointed out that most of the dust in galaxies is confined to a thin sheet coincident with the central plane of the galaxy. Hence for galaxies seen almost edge on, the near edge of the galaxy will be distinguished by dark dust lanes silhouetted against the bright nuclear bulge, whereas the dust lanes on the far edge will be much less conspicuous, since there is no background light for these lanes to obscure. The photograph of the spiral galaxy NGC 4216 at the bottom of page 41 shows the phenomenon to good advantage; there is little doubt as to which edge is closer to the viewer. When we applied this criterion to the hydrogen-alpha photograph of M 82, we found that the north side was almost certainly closer to our galaxy. It follows that the material in the filaments must be moving outward from the center of the galaxy along the axis of rotation.

Lynds's spectral measurements provided even more conclusive evidence for regarding M 82 as an exploding galaxy. He found that the greater the distance from the center of the galaxy along the axis of rotation, the more the spectral lines appeared to be inclined. He concluded that the velocity of expansion of the filaments on each side of the galactic disk must increase linearly with their distance from the center [*see illustration at right*]. Having calculated the tilt of the galaxy along the line of sight to be about eight degrees 23 minutes, Lynds and I found that the velocity of the matter at the ends of the filaments



ADDITIONAL EVIDENCE for regarding M 82 as an exploding galaxy was derived from Lynds's spectral measurements. He found that the greater the distance from the center of the galaxy along the axis of rotation, the more the spectral lines appeared to be inclined. This indicated that the velocity of expansion of the hydrogen filaments on each side of the galactic disk must increase linearly with distance from center. Short horizontal arrows represent motion along line of sight; longer arrows represent actual velocity of expansion.



POLARIZED PHOTOGRAPHS OF M 82 support the hypothesis that the gas in the filaments was originally ionized by the synchrotron process. The polarizing filters were set parallel to the plane of the galaxy in the top photograph and perpendicular to the plane of the galaxy in the bottom photograph. The photographs show that synchrotron light from the filaments is highly polarized with the electric vector of the light parallel to the plane of the galaxy. They also show that M 82 possesses a regular, large-scale magnetic field.

must be roughly 600 miles per second.

The direct relation of velocity to distance in the filaments can be taken to mean that the time required for each part of a filament to travel from a common origin to its present position must be a constant; in other words, all the matter in the filaments must have been back in the nucleus of M 82 at a given time in the past. This is strong evidence for regarding the filaments as the residue of a single vast explosion in the nucleus of the galaxy. The date of the explosion can be estimated by measuring the slope of the curve that relates velocity to distance. This method indicates that the explosion occurred some 1.5 million years before the stage we see now. (Since M 82 is roughly 10 million light-years away, the date as measured from the present on earth would be about 11.5 million years ago.) By astronomical standards 1.5 million years is an extremely short interval of time for so vast a change. Even taking into account the deceleration of the filaments due to encounters with the surrounding gas, the date of the explosion can probably be set at not more than two or three million years ago.

The amount of matter moving outward from the center of M 82 can be estimated from the strength of the hydrogen-alpha emission line in the spectrum of the filaments. By this method we were able to calculate that to produce the observed emission roughly 6×10^{63} low-energy protons and electrons must be present in the filaments. This is equivalent to roughly five million times the mass of the sun, or about a two-thousandth of the total mass of M 82. The energy needed to set this huge mass of matter in motion is about 2×10^{55} ergs.

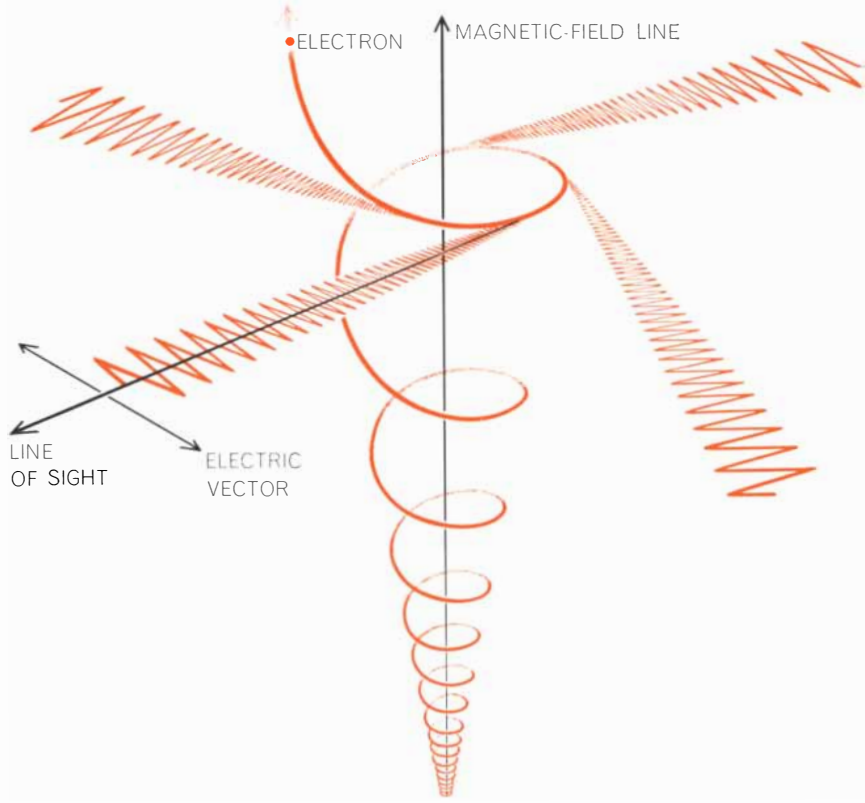
At first it was not at all clear how the hydrogen gas in the filaments became ionized. Ordinarily interstellar clouds of hydrogen are ionized only when they are in the immediate vicinity of extremely hot blue stars. Ultraviolet photons from the stars are sufficiently energetic to overcome the binding energy of the electron-proton pair in the neutral hydrogen atom. Once the gas is ionized in this manner the electrons are free to recombine with the proton nuclei, causing the emission of visible light as the electrons cascade down the various atomic energy levels [*see bottom illustration on opposite page*]. This process could not possibly be taking place in M 82: the galaxy is conspicuously free of hot blue stars, particularly in the filaments. How then could the

hydrogen gas in the filaments become ionized?

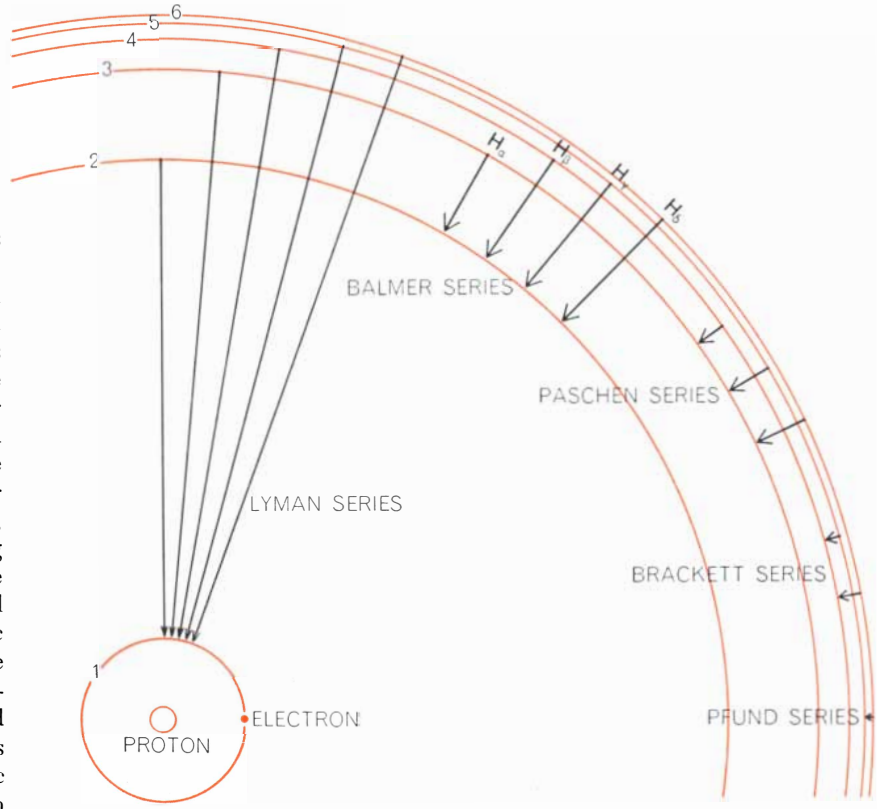
Again the exploding-galaxy hypothesis provided a tentative answer. Suppose that large numbers of relativistic electrons produced in the original galactic explosion were able to generate by the synchrotron mechanism not only the observed radio flux but also enough ultraviolet radiation to ionize the hydrogen gas in the filaments. Although it seemed incredible in 1962 that enough electrons could be produced at the required energy (10,000 bev), no other energy source appeared remotely possible.

The first evidence of the correctness of this line of reasoning was obtained early last year by Hugh M. Johnson of the Lick Observatory. Working with the 36-inch Crossley reflector, Johnson exposed four blue-sensitive plates to M 82 and printed all four plates on the same piece of photographic paper. This increased the contrast sufficiently to reveal an additional fringe of faint outer filaments on both the north and the south side of M 82. Shortly thereafter I made a new series of photographs with the 200-inch telescope. These were combined in a similar manner by William C. Miller of the Mount Wilson and Palomar Observatories, who used a new technique he had developed for increasing the contrast of the faint details without losing the features of the brighter regions. The resulting composite photographs, one of which is reproduced at the top of page 41, showed for the first time a delicate outer fringe of blue filaments that emit continuous rather than line radiation.

It was now crucial to establish if this outermost fringe of blue light was indeed produced by the synchrotron process. Fortunately it is a well-known fact that synchrotron radiation produces light that is highly polarized, with the electric vector of the light perpendicular to the lines of force in a magnetic field [*see top illustration at right*]. If the magnetic field of M 82 is regular over an appreciable portion of the filaments, photographs made through polarizing filters should not only test the existence of synchrotron radiation but also reveal the orientation of the galaxy's magnetic field. Polarized photographs were made with the 200-inch telescope in February of this year. They show beyond doubt that light from the filaments is highly polarized, with the electric vector of the synchrotron radiation parallel to the plane of the galaxy [*see illustrations on opposite page*]. Evidently M 82 possesses a regular, large-scale magnetic field aligned predomi-



SYNCHROTRON RADIATION is produced by the rapid gyration of high-energy charged particles in a magnetic field. Light generated by this process is highly polarized, with the electric vector perpendicular to both the magnetic-field line and the direction of the particle. Wavelength of the radiation depends on velocity of particle and strength of magnetic field.



IONIZED HYDROGEN ATOM emits radiation when a free electron recombines with a proton to form a neutral hydrogen atom. The wavelength of the radiation depends on how far the electron travels in each "jump" from a higher to a lower energy level; the hydrogen-alpha (H_α) emission line is produced when electron jumps from the third to second level.

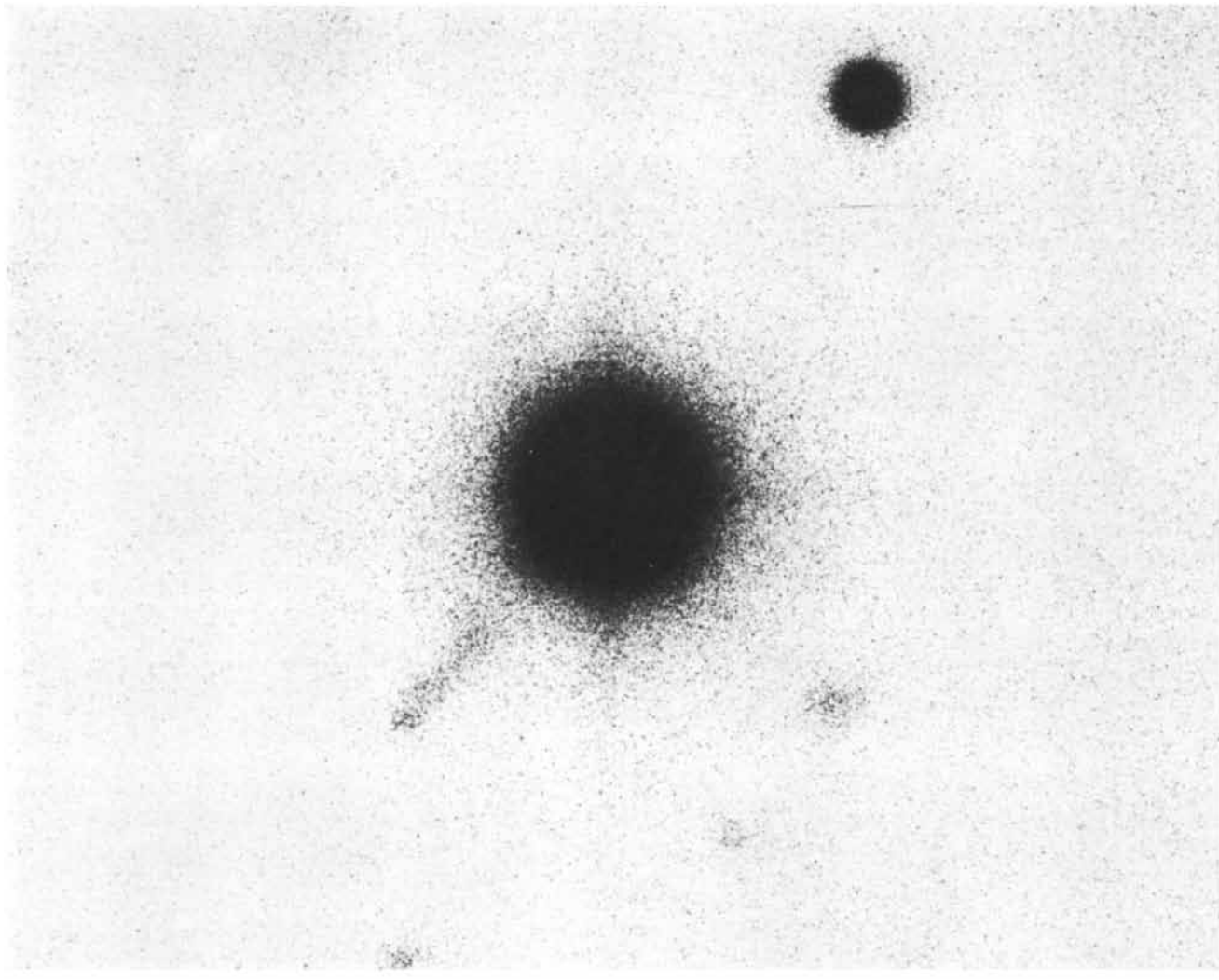
nantly along the axis of rotation on both sides of the galactic disk.

Preliminary measurements indicate that the synchrotron radiation process is sufficiently energetic to account for the ionization of the hydrogen gas in the filaments and hence for the characteristic hydrogen-alpha emission lines. Further confirmation will have to wait until measurements of the intensity of the ultraviolet radiation emitted by the filaments can be made from orbiting astronomical observatories.

Astrophysicists interested in cosmic ray research can only envy the location of their hypothetical colleagues on planets orbiting the stars in M 82. The local cosmic ray flux of electrons alone in that galaxy is about 1,000 times greater than it is around the earth. Cosmic ray protons must also be present in enormous quantities in M 82, although their presence cannot be directly observed because protons are very sluggish emitters of synchrotron radiation.

Although M 82 is undoubtedly a special case, it can in some respects be regarded as a typical radio galaxy. For example, although it does not exhibit two separate regions of radio emission, these may perhaps develop later in its history. What is more to the point, its filaments, which constitute the primary evidence for an explosion in its nucleus, have counterparts in many other radio galaxies. Jets of high-energy gas have been observed in such intense radio galaxies as M 87 and in the "quasi-stellar" radio sources 3*C* 48 and 3*C* 273. A particularly interesting example of this phenomenon can be seen in the spiral galaxy NGC 4651, which has been identified with the radio source 3*C* 275.1 [*see illustration on opposite page*]. In this galaxy two jets extend from opposite sides of a spiral arm to distances of about 50,000 light-years, where they terminate at the edge of a visible halo.

Astronomers have just begun to study exploding galaxies. Yet even at this early stage of inquiry we find that radical new ideas are needed to account for the enormous energies involved in these events. The synchrotron model enables us to calculate the total energy required to produce a galactic explosion; in the case of M 82 this input of energy amounts to about 10^{57} or 10^{58} ergs. The giant radio sources, such as Cygnus A, Hercules A and Hydra A, undoubtedly call for a considerably greater input of energy, perhaps as much as 10^{62} ergs. Herein lies the dilemma. Thermonuclear reactions, which convert hydrogen to helium, are comparatively inefficient, producing only 6×10^{18} ergs for every gram converted. Even if the conversion of mass to radio energy were 100 percent efficient, 10 billion solar masses of hydrogen would be required to produce 10^{62} ergs of radio energy. This figure, however, corresponds to the entire mass of a medium-sized galaxy! (Since con-



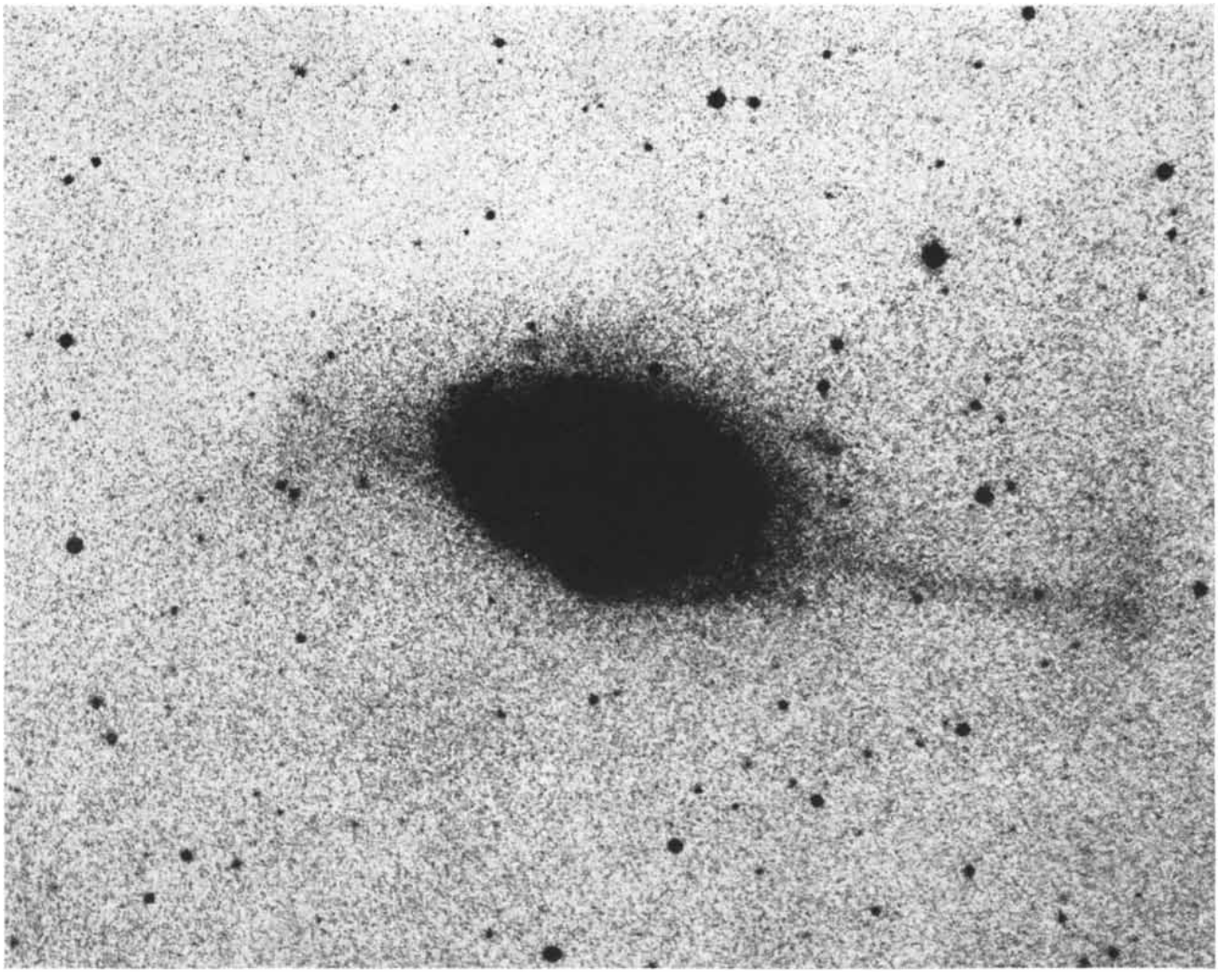
JET protrudes some 150,000 light-years beyond the outer edge of the quasi-stellar radio source designated 3*C* 273 in this photograph made with the 200-inch telescope. The jet resembles the filaments in M 82 and may be the product of a similar galactic explosion.

version efficiencies of mass to radio energy are probably not higher than 1 percent, such a thermonuclear reaction would actually require closer to a trillion solar masses.)

It is obvious that conventional energy sources are not adequate to explain the phenomenon we are observing, and some totally new energy principle may have to be devised. One possible new mechanism has recently been suggested by Fred Hoyle of the University of Cambridge and William A. Fowler of the California Institute of Technology. According to their model, when any scattered mass condenses, gravitational potential energy is released. Under certain conditions this can be a very efficient process, since the potential energy varies directly with the square of the mass and inversely with the final radius. Carried to its limit, this model predicts that if collapse is not countered by rotation, a mass of gas can condense until it ultimately disappears from view!

The disappearance of a massive object into its own gravitational field is a concept inherent in the general theory of relativity, proposed by Albert Einstein in 1916; the details of the concept were worked out a few years later by the German astronomer Karl Schwarzschild. Simply stated, the local curvature of space, which is dependent on the mass of the matter in the immediate vicinity, can ultimately close around itself and isolate its contents from the rest of the universe, provided that the density of the matter is high enough. The ultimate radius at which this envelopment occurs is given by the expression $2GM/c^2$, where G is the gravitational constant, M is the mass and c is the speed of light. This radius is called the Schwarzschild singularity, and when it is reached matter disappears entirely from view. What is important for our purpose is that when matter collapses to this radius, the energy released is equal to $\frac{1}{2}Mc^2$. Without the multiplying factor of $\frac{1}{2}$, this is equal to the annihilation energy of matter, as expressed by the familiar formula $E = Mc^2$. This process is estimated to be about 100 times more efficient than any thermonuclear reaction. An energy of 10^{62} ergs would be produced if only 100 million solar masses were to collapse to the Schwarzschild radius.

It is only fair to say that no one knows if this kind of gravitational collapse is actually possible, or if it is, what mechanism could account for the exchange of energy from the gravitational field to the relativistic particles needed to produce the observed radio emission. In any event the discovery of exploding galaxies has presented both astronomers and physicists with problems of fundamental importance and complexity. Observations over the next few years may illuminate at least part of the mystery presented by these spectacular events, which are by far the most energetic ever perceived by man.



TWIN JETS extending outward about 50,000 light-years from opposite sides of a spiral arm in the intense radio galaxy NGC 4651 also resemble the hydrogen filaments ejected in the explosion of M 82. The jets terminate at the edge of a barely visible halo.

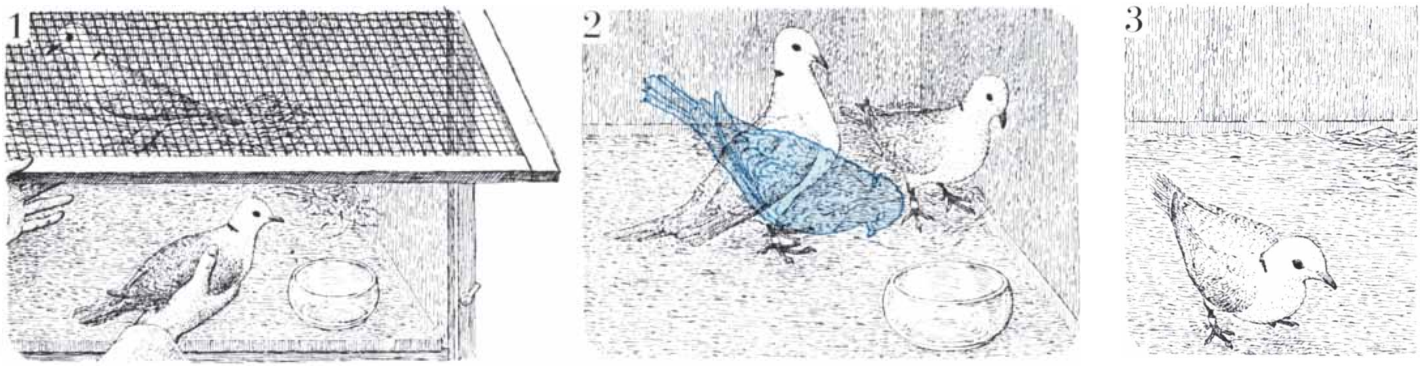
The Reproductive Behavior of Ring Doves

An account of experiments showing that the changes in activity that constitute the behavior cycle are governed by interactions of outside stimuli, the hormones and the behavior of each mate

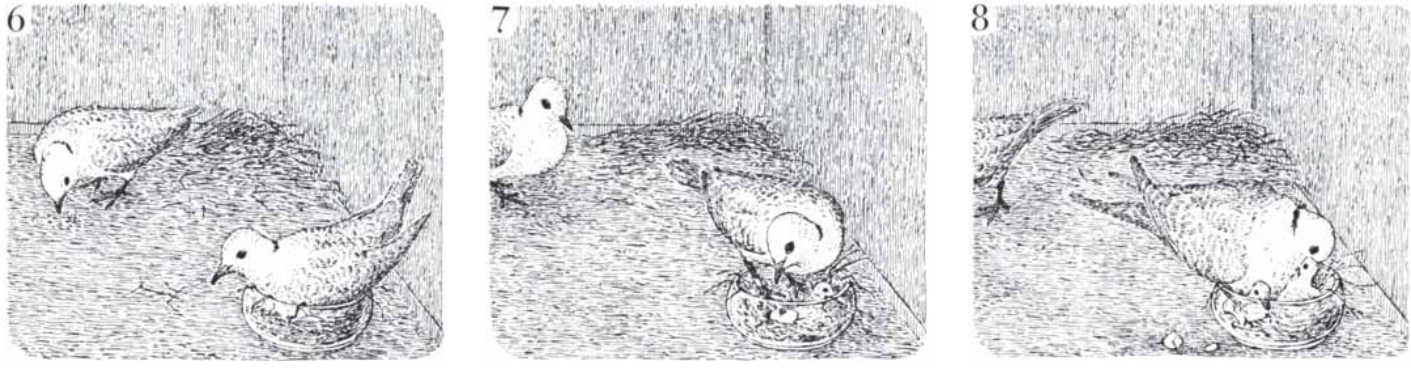
by Daniel S. Lehrman

In recent years the study of animal behavior has proceeded along two different lines, with two groups of investigators formulating problems in different ways and indeed approaching the problems from different points of view. The comparative psychologist traditionally tends first to ask a question and then to attack it by way of animal experimentation. The ethologist, on the other hand, usually begins by observing the normal activity of an animal and then seeks to identify and analyze specific behavior patterns characteristic of the species.

The two attitudes can be combined. The psychologist can begin, like the ethologist, by watching an animal do what it does naturally, and only then ask questions that flow from his observations. He can go on to manipulate experimental conditions in an effort to discover the psychological and biological events that give rise to the behavior under study and perhaps to that of other animals as well. At the Institute of Animal Behavior at Rutgers University we have taken this approach to study in detail the reproductive-behavior cycle of the ring dove (*Streptopelia risoria*). The highly specific changes in behavior that occur in the course of the cycle, we find, are governed by complex psycho-



REPRODUCTIVE-BEHAVIOR CYCLE begins soon after a male and a female ring dove are introduced into a cage containing nesting material (hay in this case) and an empty glass nest bowl (*1*). Courtship activity, on the first day, is characterized by the "bowing



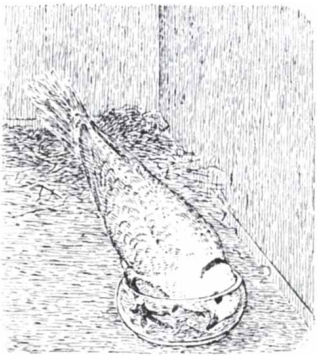
CYCLE CONTINUES as the adult birds take turns incubating the eggs (*6*), which hatch after about 14 days (*7*). The newly hatched squabs are fed "crop-milk," a liquid secreted in the gullets of the adults (*8*). The parents continue to feed them, albeit reluctantly,

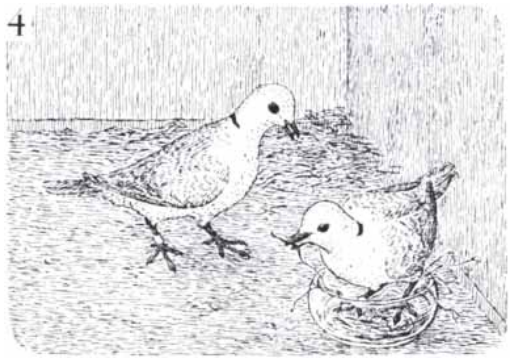
biological interactions of the birds' inner and outer environments.

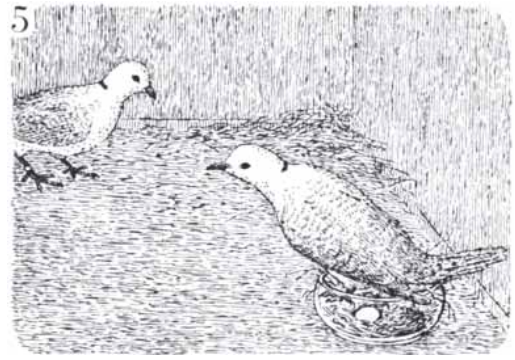
The ring dove, a small relative of the domestic pigeon, has a light gray back, creamy underparts and a black semicircle (the "ring") around the back of its neck. The male and female look alike and can only be distinguished by surgical exploration. If we place a male and a female ring dove with previous breeding experience in a cage containing an empty glass bowl and a supply of nesting material, the birds invariably enter on their normal behavioral cycle, which follows a predictable course and a fairly regular time schedule. During the first day the principal activity is courtship: the male struts around, bowing and cooing at the female. After several hours the birds announce their selection of a nest site (which in nature would be a concave place and in our cages is the glass bowl) by crouching in it and uttering a distinctive coo. Both birds participate in building the nest, the male usually gathering material and carrying it to the female, who stands in the bowl and constructs the nest. After a week or more of nest-building, in the course of which the birds copulate, the female becomes noticeably more attached to the nest and difficult to dislodge; if one attempts to lift her off the nest, she may grasp it with her claws and take it along. This behavior usually indicates that the female is about to lay her eggs. Between seven and 11 days after the beginning of the courtship she produces her first egg, usually at about five o'clock in the afternoon. The female dove sits on the egg and then lays a second one, usually at about nine o'clock in the morning two days later. Sometime that day the male takes a turn sitting; thereafter the two birds alternate, the male sitting for about six hours in the middle of each day, the female for the remaining 18 hours a day.

In about 14 days the eggs hatch and the parents begin to feed their young "crop-milk," a liquid secreted at this stage of the cycle by the lining of the adult dove's crop, a pouch in the bird's gullet. When they are 10 or 12 days old, the squabs leave the cage, but they continue to beg for and to receive food from the parents. This continues until the squabs are about two weeks old, when the parents become less and less willing to feed them as the young birds gradually develop the ability to peck for grain on the floor of the cage. When the young are about 15 to 25 days old, the adult male begins once again to bow and coo; nest-building is resumed, a new clutch of eggs is laid and the cycle is repeated. The entire cycle lasts about six or seven weeks and—at least in our laboratory, where it is always spring because of controlled light and temperature conditions—it can continue throughout the year.

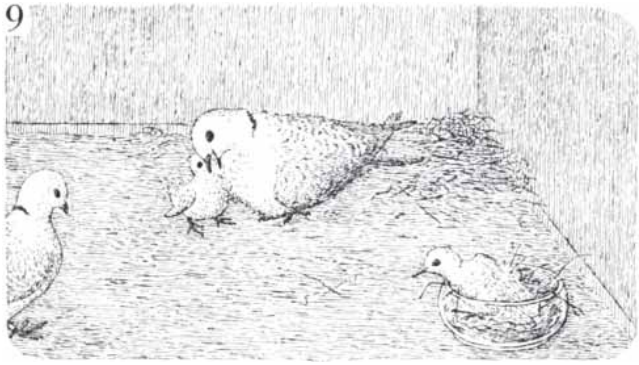
The variations in behavior that constitute the cycle are not merely casual or superficial changes in the birds' preoccupations; they represent striking changes in the overall pattern of activity and in the atmosphere of the breeding cage. At its appropriate stage each of the kinds of behavior I have described represents the predominant activity of the animals at the time. Furthermore, these changes in behavior are not just responses to changes in the external situation. The birds do not build the nest merely because the nesting material is available; even if nesting material is in the cage throughout the cycle, nest-building behavior is concentrated,

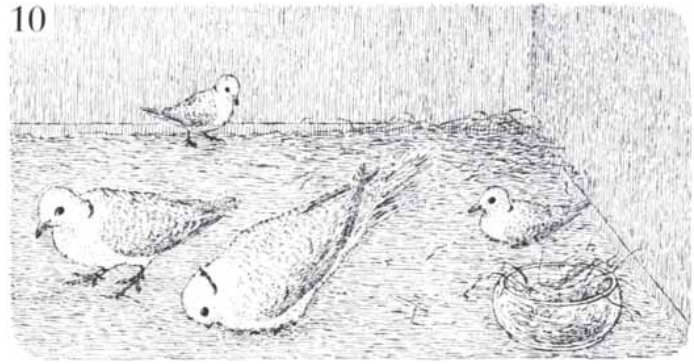






coo" of the male (*2*). The male and then the female utter a distinctive "nest call" to indicate their selection of a nesting site (*3*). There follows a week or more of cooperation in nest-building (*4*), culminating in the laying of two eggs at precise times of day (*5*).





as the young birds learn to peck for grain themselves (*9*). When the squabs are between two and three weeks old, the adults ignore them and start to court once again, and a new cycle begins (*10*). Physical changes during the cycle are shown on the next page.

as described, at one stage. Similarly, the birds react to the eggs and to the young only at appropriate stages in the cycle.

These cyclic changes in behavior therefore represent, at least in part, changes in the internal condition of the animals rather than merely changes in their external situation. Furthermore, the changes in behavior are associated with equally striking and equally pervasive changes in the anatomy and the physiological state of the birds. For example, when the female dove is first introduced into the cage, her oviduct weighs some 800 milligrams. Eight or nine days later, when she lays her first egg, the oviduct may weigh 4,000 milligrams. The crops of both the male and the female weigh some 900 milligrams when the birds are placed in the cage, and when they start to sit on the eggs some 10 days later they still weigh about the same. But two weeks afterward, when the eggs hatch, the parents' crops may weigh as much as 3,000 milligrams. Equally striking changes in the condition of the ovary, the weight of the testes, the length of the gut, the weight of the liver, the microscopic structure of the pituitary gland and other physiological indices are correlated with the behavioral cycle.

Now, if a male or a female dove is placed alone in a cage with nesting material, no such cycle of behavioral or anatomical changes takes place. Far from producing two eggs every six or seven weeks, a female alone in a cage lays no eggs at all. A male alone shows no interest when we offer it nesting material, eggs or young. The cycle of psychobiological changes I have described is, then, one that occurs more or less synchronously in each member of a pair of doves living together but that will not occur independently in either of the pair living alone.

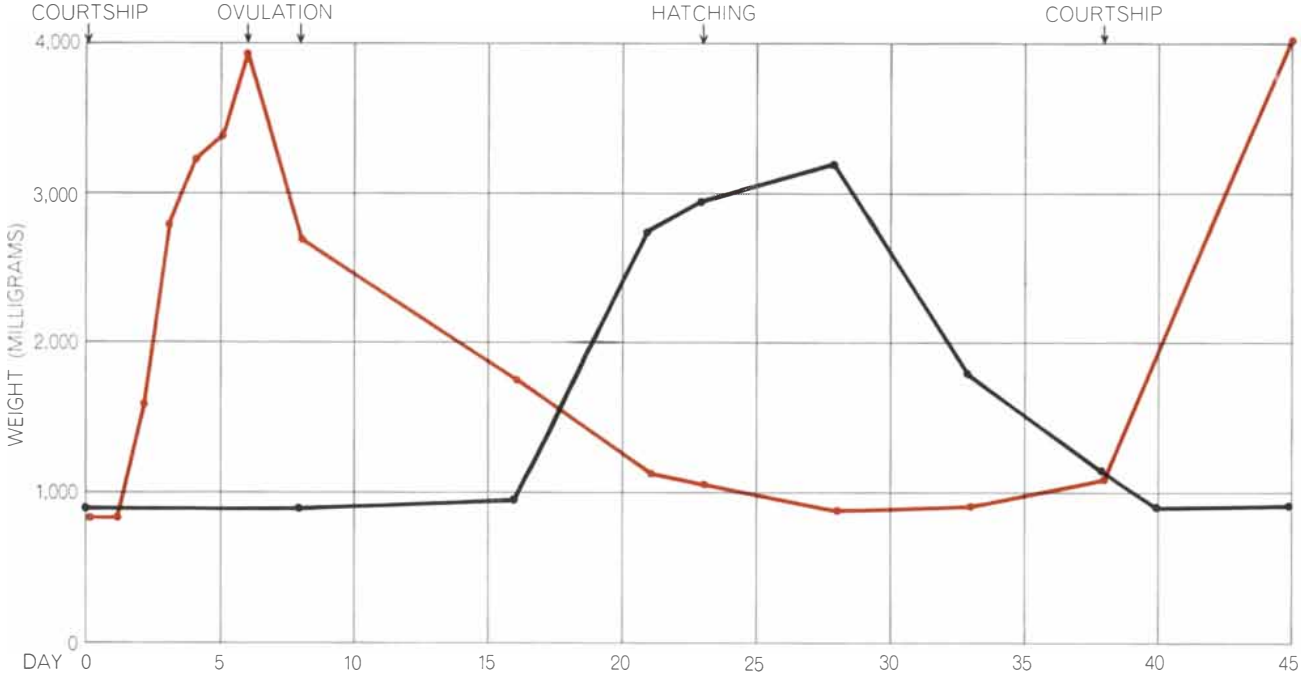
In a normal breeding cycle both the male and the female sit on the eggs almost immediately after they are laid. The first question we asked ourselves was whether this is because the birds are always ready to sit on eggs or because they come into some special condition of readiness to incubate at about the time the eggs are produced.

We kept male and female doves in isolation for several weeks and then placed male-female pairs in test cages, each supplied with a nest bowl containing a normal dove nest with two eggs. The birds did not sit; they acted almost as if the eggs were not there. They courted, then built their own nest (usually on top of the planted nest and its eggs, which we had to keep fishing out to keep the stimulus situation constant!), then finally sat on the eggs—five to seven days after they had first encountered each other.

This clearly indicated that the doves are not always ready to sit on eggs; under the experimental conditions they changed from birds that did not want to incubate to birds that did want to incubate in five to seven days. What had induced this change? It could not have been merely the passage of time since their last breeding experience, because this had varied from four to six or more weeks in different pairs, whereas the variation in time spent in the test cage before sitting was only a couple of days.

Could the delay of five to seven days represent the time required for the birds to get over the stress of being handled and become accustomed to the strange cage? To test this possibility we placed pairs of doves in cages without any nest bowls or nesting material and separated each male and female by an opaque partition. After seven days we removed the partition and introduced nesting material and a formed nest with eggs. If the birds had merely needed time to recover from being handled and become acclimated to the cage, they should now have sat on the eggs immediately. They did not do so; they sat only after five to seven days, just as if they had been introduced into the cage only when the opaque partition was removed.

The next possibility we considered was that in this artificial situation stimulation from the eggs might induce the change from a nonsitting to a sitting "mood" but that this effect required five to seven days to reach a threshold value at which the behavior would change.



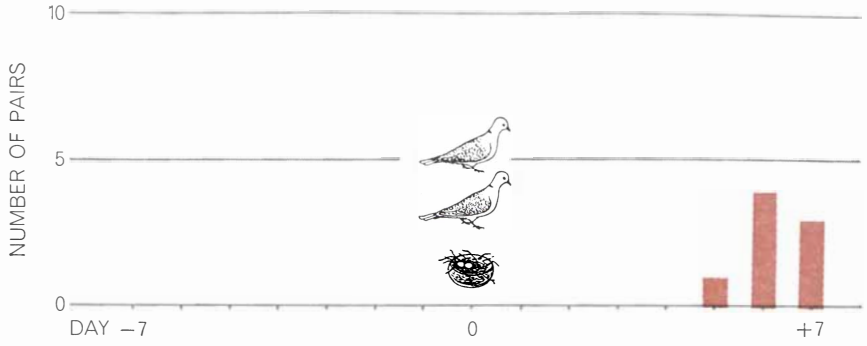
ANATOMICAL AND PHYSIOLOGICAL changes are associated with the behavioral changes of the cycle. The chart gives average weights of the crop (*black curve*) and the female oviduct (*color*) at various stages measured in days after the beginning of courtship.

We therefore placed pairs of birds in test cages with empty nest bowls and a supply of nesting material but no eggs. The birds courted and built nests. After seven days we removed the nest bowl and its nest and replaced it with a fresh bowl containing a nest and eggs. All these birds sat within two hours.

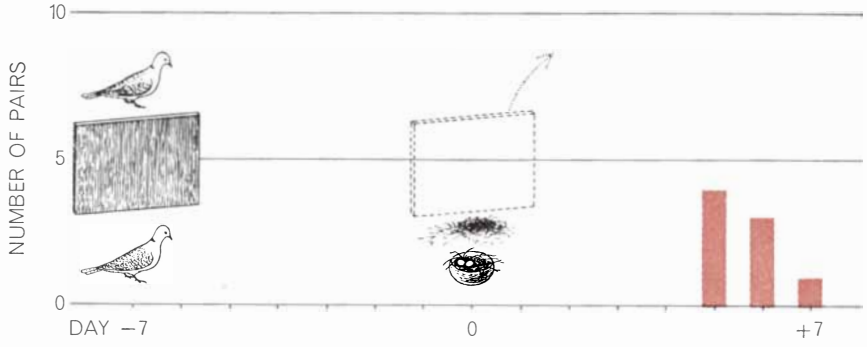
It was now apparent that some combination of influences arising from the presence of the mate and the availability of the nest bowl and nesting material induced the change from nonreadiness to incubate to readiness. In order to distinguish between these influences we put a new group of pairs of doves in test cages without any nest bowl or nesting material. When, seven days later, we offered these birds nesting material and nests with eggs, most of them did not sit immediately. Nor did they wait the full five to seven days to do so; they sat after one day, during which they engaged in intensive nest-building. A final group, placed singly in cages with nests and eggs, failed to incubate at all, even after weeks in the cages.

In summary, the doves do not build nests as soon as they are introduced into a cage containing nesting material, but they will do so immediately if the nesting material is introduced for the first time after they have spent a while together; they will not sit immediately on eggs offered after the birds have been in a bare cage together for some days, but they will do so if they were able to do some nest-building during the end of their period together. From these experiments it is apparent that there are two kinds of change induced in these birds: first, they are changed from birds primarily interested in courtship to birds primarily interested in nest-building, and this change is brought about by stimulation arising from association with a mate; second, under these conditions they are further changed from birds primarily interested in nest-building to birds interested in sitting on eggs, and this change is encouraged by participation in nest-building.

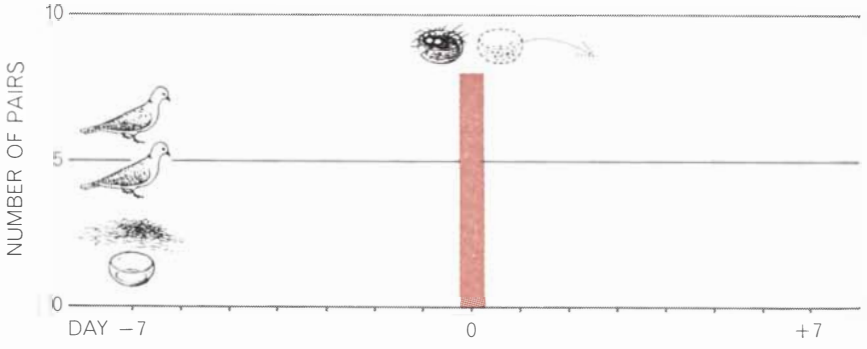
The course of development of readiness to incubate is shown graphically by the results of another experiment, which Philip N. Brody, Rochelle Wortis and I undertook shortly after the ones just described. We placed pairs of birds in test cages for varying numbers of days, in some cases with and in others without a nest bowl and nesting material. Then we introduced a nest and eggs into the cage. If neither bird sat within three hours, the test was scored as nega-



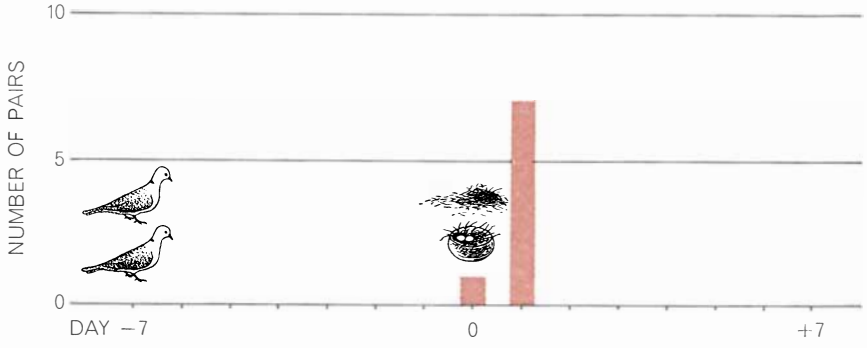
READINESS TO INCUBATE was tested with four groups of eight pairs of doves. Birds of the first group were placed in a cage containing a nest and eggs. They went through courtship and nest-building behavior before finally sitting after between five and seven days.



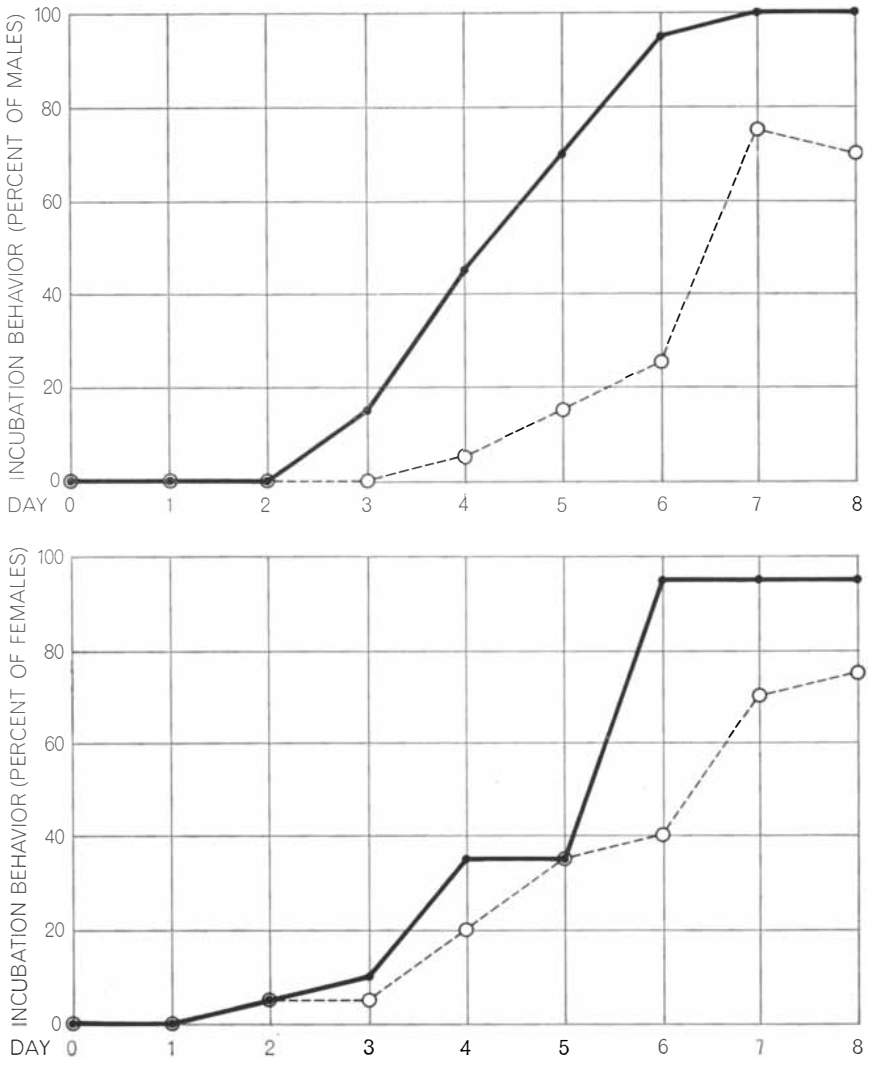
EFFECT OF HABITUATION was tested by keeping two birds separated for seven days in the cage before introducing nest and eggs. They still sat only after five to seven days.



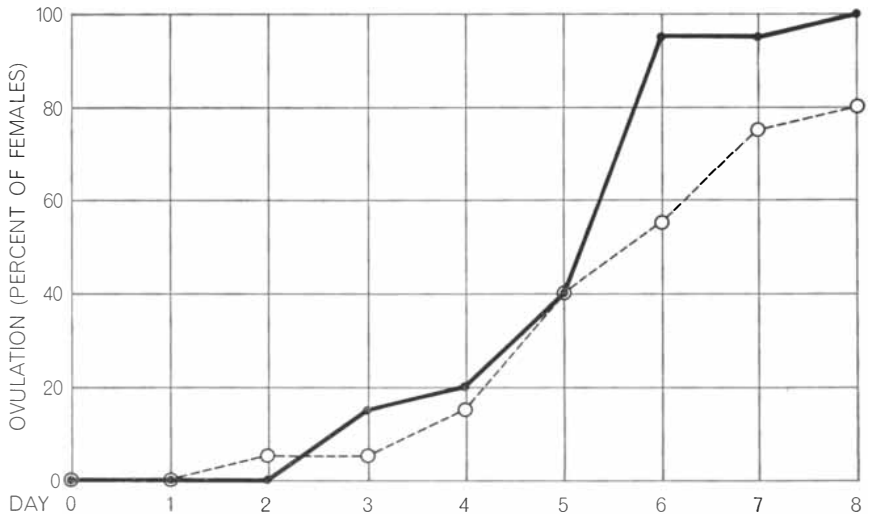
MATE AND NESTING MATERIAL had a dramatic effect on incubation-readiness. Pairs that had spent seven days in courtship and nest-building sat as soon as eggs were offered.



PRESENCE OF MATE without nesting activity had less effect. Birds that spent a week in cages with no nest bowls or hay took a day to sit after nests with eggs were introduced.



DURATION OF ASSOCIATION with mate and nesting material affects incubation behavior. The abscissas give the length of the association for different groups of birds. The plotted points show what percentage of each group sat within three hours of being offered eggs. The percentage increases for males (*top*) and females (*bottom*) as a function of time previously spent with mate (*open circles*) or with mate and nesting material (*solid dots*).



OVULATION is similarly affected. These curves, coinciding closely with those of the bottom chart above, show the occurrence of ovulation in the same birds represented there.

tive and both birds were removed for autopsy. If either bird sat within three hours, that bird was removed and the other bird was given an additional three hours to sit. The experiment therefore tested—independently for the male and the female—the development of readiness to incubate as a function of the number of days spent with the mate, with or without the opportunity to build a nest.

It is apparent [*see top illustration at left*] that association with the mate gradually brings the birds into a condition of readiness to incubate and that this effect is greatly enhanced by the presence of nesting material. Exposure to the nesting situation does not stimulate the onset of readiness to incubate in an all-or-nothing way; rather, its effect is additive with the effect of stimulation provided by the mate. Other experiments show, moreover, that the stimulation from the mate and nesting material is sustained. If either is removed, the incidence of incubation behavior decreases.

The experiments described so far made it clear that external stimuli normally associated with the breeding situation play an important role in inducing a state of readiness to incubate. We next asked what this state consists of physiologically. As a first approach to this problem we attempted to induce incubation behavior by injecting hormones into the birds instead of by manipulating the external stimulation. We treated birds just as we had in the first experiment but injected some of the birds with hormones while they were in isolation, starting one week before they were due to be placed in pairs in the test cages. When both members of the pair had been injected with the ovarian hormone progesterone, more than 90 percent of the eggs were covered by one of the birds within three hours after their introduction into the cage instead of five to seven days later. When the injected substance was another ovarian hormone—estrogen—the effect on most birds was to make them incubate after a latent period of one to three days, during which they engaged in nest-building behavior. The male hormone testosterone had no effect on incubation behavior.

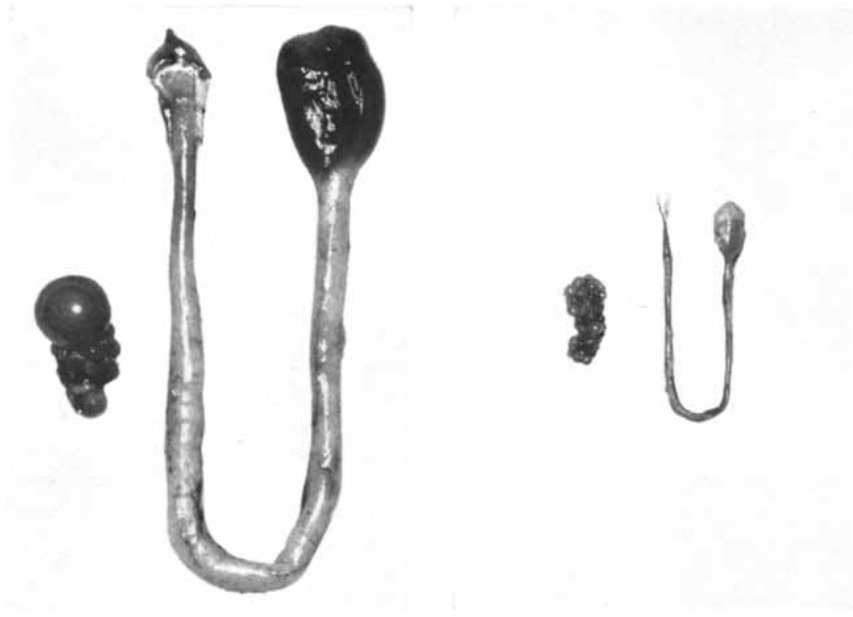
During the 14 days when the doves are sitting on the eggs, their crops increase enormously in weight. Crop growth is a reliable indicator of the secretion of the hormone prolactin by the birds' pituitary glands. Since this

growth coincides with the development of incubation behavior and culminates in the secretion of the crop-milk the birds feed to their young after the eggs hatch, Brody and I have recently examined the effect of injected prolactin on incubation behavior. We find that prolactin is not so effective as progesterone in inducing incubation behavior, even at dosage levels that induce full development of the crop. For example, a total prolactin dose of 400 international units induced only 40 percent of the birds to sit on eggs early, even though their average crop weight was about 3,000 milligrams, or more than three times the normal weight. Injection of 10 units of the hormone induced significant increases in crop weight (to 1,200 milligrams) but no increase in the frequency of incubation behavior. These results, together with the fact that in a normal breeding cycle the crop begins to increase in weight only after incubation begins, make it unlikely that prolactin plays an important role in the initiation of normal incubation behavior in this species. It does, however, seem to help to maintain such behavior until the eggs hatch.

Prolactin is much more effective in inducing ring doves to show regurgitation-feeding responses to squabs. When 12 adult doves with previous breeding experience were each injected with 450 units of prolactin over a seven-day period and placed, one bird at a time, in cages with squabs, 10 of the 12 fed the squabs from their engorged crops, whereas none of 12 uninjected controls did so or even made any parental approaches to the squabs.

This experiment showed that prolactin, which is normally present in considerable quantities in the parents when the eggs hatch, does contribute to the doves' ability to show parental feeding behavior. I originally interpreted it to mean that the prolactin-induced engorgement of the crop was necessary in order for any regurgitation feeding to take place, but E. Klinghammer and E. H. Hess of the University of Chicago have correctly pointed out that this was an error, that ring doves are capable of feeding young if presented with them rather early in the incubation period. They do so even though they have no crop-milk, feeding a mixture of regurgitated seeds and a liquid. We are now studying the question of how early the birds can do this and how this ability is related to the onset of prolactin secretion.

The work with gonad-stimulating hormones and prolactin demonstrates that the various hormones successively produced by the birds' glands during their reproductive cycle are capable of inducing the successive behavioral changes that characterize the cycle.



REPRODUCTIVE ORGANS of the female develop if she is in the same cage as a male (even if separated from him by a glass partition) provided he acts like a male. These photographs, made to the same scale, compare the ovary and oviduct (*left*) of a female exposed to an intact male for seven days with organs (*right*) of a female exposed to a castrated male.

Up to this point I have described two main groups of experiments. One group demonstrates that external stimuli induce changes in behavioral status of a kind normally associated with the progress of the reproductive cycle; the second shows that these behavioral changes can also be induced by hormone administration, provided that the choice of hormones is guided by knowledge of the succession of hormone secretions during a normal reproductive cycle. An obvious—and challenging—implication of these results is that external stimuli may induce changes in hormone secretion, and that environment-induced hormone secretion may constitute an integral part of the mechanism of the reproductive behavior cycle. We have attacked the problem of the environmental stimulation of hormone secretion in a series of experiments in which, in addition to examining the effects of external stimuli on the birds' behavioral status, we have examined their effects on well-established anatomical indicators of the presence of various hormones.

Background for this work was provided by two classic experiments with the domestic pigeon, published during the 1930's, which we have verified in the ring dove. At the London Zoo, L. H. Matthews found that a female pigeon would lay eggs as a result of being placed in a cage with a male from whom she was separated by a glass plate. This was an unequivocal demonstration that visual and/or auditory stimulation provided by the male induces ovarian development in the female. (Birds are quite insensitive to olfactory stimulation.) And M. D. Patel of the University of Wisconsin found that the crops of breeding pigeons, which develop strikingly during the incubation period, would regress to their resting state if the incubating birds were removed from their nests and would fail to develop at all if the birds were removed before crop growth had begun. If, however, a male pigeon, after being removed from his nest, was placed in an adjacent cage from which he could see his mate still sitting on the eggs, his crop would develop just as if he were himself incubating! Clearly stimuli arising from participation in incubation, including visual stimuli, cause the doves' pituitary glands to secrete prolactin.

Our autopsies showed that the incidence of ovulation in females that had associated with males for various periods coincided closely with the incidence of incubation behavior [*see bottom illustration on opposite page*]; statistical

analysis reveals a very high degree of association. The process by which the dove's ovary develops to the point of ovulation includes a period of estrogen secretion followed by one of progesterone secretion, both induced by appropriate ovary-stimulating hormones from the pituitary gland. We therefore conclude that stimuli provided by the male, augmented by the presence of the nest bowl and nesting material, induce the secretion of gonad-stimulating hormones by the female's pituitary, and that the onset of readiness to incubate is a result of this process.

As I have indicated, ovarian development, culminating in ovulation and egg-laying, can be induced in a female dove merely as a result of her seeing a male through a glass plate. Is this the result of the mere presence of another bird or of something the male does because he is a male? Carl Erickson and I have begun to deal with this question. We placed 40 female doves in separate cages, each separated from a male by a glass plate. Twenty of the stimulus animals were normal, intact males, whereas the remaining 20 had been castrated several weeks before. The intact males all exhibited vigorous bow-cooing immediately on being placed in the cage, whereas none of the castrates did so. Thirteen of the 20 females with intact males ovulated during the next seven days, whereas only two of those with the castrates did so. Clearly ovarian development in the female is not induced merely by seeing another bird but by seeing or hearing it act like a male as the result of the effects of its own male hormone on its nervous system.

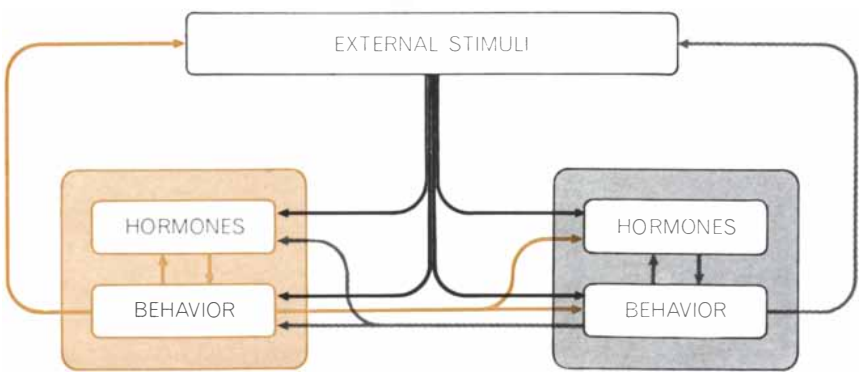
Although crop growth, which begins early in the incubation period, is apparently stimulated by participation in incubation, the crop continues to be large and actively secreting for quite some time after the hatching of the eggs. This suggests that stimuli provided by the squabs may also stimulate prolactin secretion. In our laboratory Ernst Hansen substituted three-day-old squabs for eggs in various stages of incubation and after four days compared the adults' crop weights with those of birds that had continued to sit on their eggs during the four days. He found that the crops grow even faster when squabs are in the nest than when the adults are under the influence of the eggs; the presence of squabs can stimulate a dove's pituitary glands to secrete more prolactin even before the stage in the cycle when the squabs normally appear.

This does not mean, however, that any of the stimuli we have used can induce hormone secretion at *any* time, regardless of the bird's physiological condition. If we place a pair of ring doves in a cage and allow them to go through the normal cycle until they have been sitting on eggs for, say, six days and we then place a glass partition in the cage to separate the male from the female and the nest, the female will continue to sit on the eggs and the male's crop will continue to develop just as if he were himself incubating. This is a simple replication of one of Patel's experiments. Miriam Friedman and I have found, however, that if the male and female are separated from the beginning, so that the female must build the nest by herself and sit alone from the beginning, the crop of the male does not grow. By inserting the glass plate at various times during the cycle in different groups of birds, we have found that the crop of the male develops fully only if he is not separated from the female until 72 hours or more after the second egg is laid. This means that the sight of the female incubating induces prolactin secretion in the male only if he is in the physiological condition to which participation in nest-building brings him. External stimuli associated with the breeding situation do indeed induce changes in hormone secretion.

The experiments summarized here point to the conclusion that changes in the activity of the endocrine system are induced or facilitated by stimuli coming from various aspects of the environment at different stages of the breeding cycle, and that these changes in hormone secretion induce changes in behavior that may themselves be a source of further stimulation.

The regulation of the reproductive cycle of the ring dove appears to depend, at least in part, on a double set of reciprocal interrelations. First, there is an interaction of the effects of hormones on behavior and the effects of external stimuli—including those that arise from the behavior of the animal and its mate—on the secretion of hormones. Second, there is a complicated reciprocal relation between the effects of the presence and behavior of one mate on the endocrine system of the other and the effects of the presence and behavior of the second bird (including those aspects of its behavior induced by these endocrine effects) back on the endocrine system of the first. The occurrence in each member of the pair of a cycle found in neither bird in isolation, and the synchronization of the cycles in the two mates, can now readily be understood as consequences of this interaction of the inner and outer environments.

The physiological explanation of these phenomena lies partly in the fact that the activity of the pituitary gland, which secretes prolactin and the gonad-stimulating hormones, is largely controlled by the nervous system through the hypothalamus. The precise neural mechanisms for any complex response are still deeply mysterious, but physiological knowledge of the brain-pituitary link is sufficiently detailed and definite so that the occurrence of a specific hormonal response to a specific external stimulus is at least no more mysterious than any other stimulus-response relation. We are currently exploring these responses in more detail, seeking to learn, among other things, the precise sites at which the various hormones act. And we have begun to investigate another aspect of the problem: the effect of previous experience on a bird's reproductive behavior and the interactions between these experiential influences and the hormonal effects.



INTERACTIONS that appear to govern the reproductive-behavior cycle are suggested here. Hormones regulate behavior and are themselves affected by behavioral and other stimuli. And the behavior of each bird affects the hormones and the behavior of its mate.

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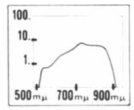
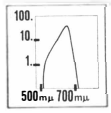
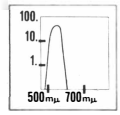
An energy distribution like 

will come out red; 

, green; and 

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And to whom are we all indebted? In part, to the U. S. Congress for voting tax money to help the coal industry compete in liquid fuels. In carrying out this mandate of the people, the U. S. Bureau of Mines found trimethylsilyl derivatives useful in analysis, identification, and purification of phenols and pointed out the applicability of GLC to the problem. True, the Bureau was probably being influenced by organosilicon research sponsored by a glass company and two other big companies that happen to make silicones. A man from one of the latter had gone so far as to suggest that trialkylsilyl derivatives of alcohols and phenols are low-viscosity liquids easy to prepare, thermally stable, resistant to air oxidation, and easy to hydrolyze.

There is also another use for EASTMAN 9151 ($14.65 for 25 grams) in GLC. It inactivates the support materials against adsorption of the gaseous solute in competition with the stationary-phase liquid. This was discovered in the non-political, non-commercial, prestige-covered halls of Cambridge University, alma mater to Isaac Newton. The boys were grinding up firebrick and taking their lead from the U. S. Bureau of Mines on the affinity of hexamethyldisilazane for the hydroxyls in the stuff.

To find out about all *the* EASTMAN *Organic Chemicals and their prices, write Distillation Products Industries, Rochester, N. Y. 14603 (Division of Eastman Kodak Company).*

* We kiss as follows: to 10 mg. of material, add 1.0 ml. of *Pyridine* (EASTMAN 214), 0.2 ml. of EASTMAN 9151 and 0.1 ml. of *Chlorotrimethylsilane* (EASTMAN P8710). Shake for 30 sec. and let stand for 5 min. while NH_4Cl precipitate settles. Take aliquot for GLC. To save for future reference, continue washing with alternate 5 ml. portions of water and *Hexane* (EASTMAN P1135) until pyridine odor is gone.

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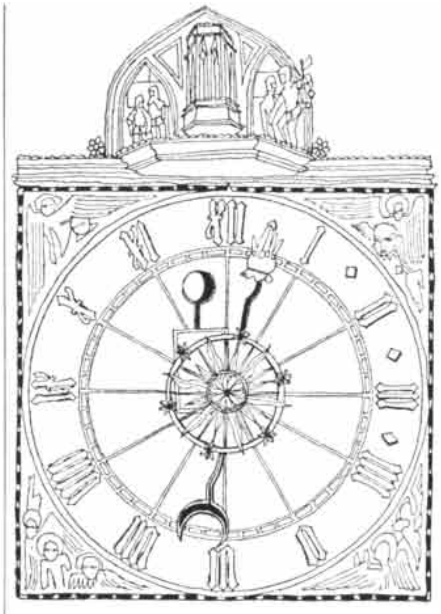
SCIENCE AND



Coming of Nuclear Age

Twenty-five years after the uranium atom was split and 22 years after the first controlled nuclear chain reaction was achieved, the third United Nations conference on the peaceful uses of atomic energy has confidently proclaimed "the beginning of the age of nuclear power." These were the words that Glenn T. Seaborg, chairman of the U.S. Atomic Energy Commission, used to characterize the 10-day meeting in Geneva at which delegates from 77 countries delivered almost 800 papers, most of them dealing with the technology and economics of fission-reactor stations. The conference was heavily attended by representatives of industry. V. S. Emelyanov of the U.S.S.R., the president of the conference, said: "This is a very good thing. If the representatives of industry show interest in scientific research, that means that industry scents the savor of a hot meal."

Many of the papers made it clear that the cost of nuclear power has been brought to a level at which it can compete with conventional fuels in many parts of the world. The reasons include reduced fuel costs, more efficient reactor operation and improved steam-turbine systems. Moreover, experience has shown that many plants can be operated at power levels higher than their design ratings. The projected Oyster Creek plant in New Jersey, for example, is designed for a minimum output of 515 megawatts but may achieve 640; power from this plant may be as inexpensive as four mills per kilowatt-hour, which would be competitive with electricity from a new conventional plant in the area. In India the Tarapur plant, now under construction near Bombay, is expected to produce power at 6.76 mills per kilowatt-hour—less than the cost of electricity from a coal-fired plant and about the same as that from an oil-fired station.

Summing up the conference, Seaborg suggested that nuclear power is developing in three phases. In the current stage a number of first-generation reactor types have come of age technologically and economically. The second phase will see the development of "converter" reactors in which nonfissionable natural uranium is turned into fissionable fuel. The third phase may see the advent of "breeder" reactors that make more fuel than they consume. The world's installed nuclear capacity has grown from five megawatts in 1955 to almost 5,000 megawatts today; it is expected to reach 25,000 megawatts in 1970 and more than 150,000 megawatts 10 years later. By the end of the century, several delegates predicted, more than half of the world's electricity will be generated in nuclear plants.

These projections are for fission reactors; they do not assume the development of a practical method of producing controlled thermonuclear power. The conference heard a number of reports of progress in fusion research but, Seaborg said, "the prospects for an easy engineering shortcut to controlled fusion are not bright... controlled fusion is one of the most difficult scientific and engineering problems ever encountered." A practical fusion reaction requires that an ionized gas be compressed to a sufficient density and heated to a high enough temperature for a long enough time to permit atoms of a light element such as hydrogen to fuse. The trouble, Seaborg said, is that whereas any one experimental fusion device may now approach the required density or temperature or duration, so far no one machine has been able to do all three things at once.

Three-Color Vision (Cont.)

Early this year two groups of workers identified red-, green- and blue-sensitive pigments in the individual

cone cells of retinas from the human eye, thus confirming a hypothesis of color vision first proposed by Thomas Young in 1801. It remained to be shown, however, that the absorption characteristics of the three pigments agreed with the color sensitivity of the living human eye. This has now been accomplished and reported in *Science* by George Wald of Harvard University. Together with Paul K. Brown, Wald had published one of the two earlier papers on the light-sensitivity of cone pigments.

Over the years many workers had tried to measure the spectral sensitivity of the functioning human eye, hoping to prove (or disprove) that it has receptors preferentially sensitive to wavelengths in three distinct regions of the spectrum. Although it was expected that the receptors would be most sensitive to red, green and blue, many other color combinations would satisfy the demands of most color-vision observations. Spectral-sensitivity measurements proved difficult to make; various investigators, working under different conditions, obtained different curves purporting to show the response of the eye's color receptors. It was particularly difficult to find evidence for a blue receptor (see "Visual Pigments in Man," by W. A. H. Rushton; SCIENTIFIC AMERICAN, November, 1962).

To make his measurements Wald had his subjects view flashes of monochromatic light against backgrounds of various colors and intensities. Depending on the background, the eye could be fatigued at certain wavelengths, thus enabling Wald to measure its sensitivity over the full spectrum of remaining wavelengths. "The isolation of individual spectral sensitivity curves [of receptors] by these methods involves trying numbers of filters and brightnesses," Wald reported. "The conditions finally chosen were those that yielded the narrowest and simplest shapes of spectral sensitivity function, on the assumption that these criteria should mark the most complete isolations."

Not only did Wald identify a blue receptor but also his results for all three receptors were in remarkably close agreement with his previous measurements of the light-sensitive pigments in single cones. Those measurements

showed a maximum blue absorption at 450 millimicrons, a green maximum at 525 millimicrons and a red maximum at 555. Wald's new sensory measurements, when corrected slightly for the pigmentation of various eye tissues, show maximum spectral sensitivities at 430, 540 and 575 millimicrons.

Wald notes in his paper that the British investigator W. S. Stiles had "come closest to solving this problem by sensory methods" but had not published all his results. Stiles's maximum for the three color receptors (published in an appendix to Wald's paper) are at 443, 533 and 590 millimicrons. With this close agreement between pigment-absorption measurements in isolated cones and sensory measurements in the living eye the three-color theory of vision can probably be regarded, after 163 years of investigation and debate, as settled.

Twinkling Quasars

A new type of rapid scintillation has been detected in quasi-stellar radio sources, the recently discovered astronomical curiosities that include the most energetic and distant objects in the universe. These objects, sometimes called quasars, fluctuate randomly in intensity by as much as 60 percent in a period of one or two seconds. This rapid fluctuation, first noticed by radio astronomers at the University of Cambridge, is superimposed on a more gradual fluctuation that extends over a period of weeks or months.

The slower fluctuation is still a mystery, but the rapid one is evidently caused by the solar wind, the tenuous stream of charged particles driven outward from the sun. The solar wind creates turbulence in interplanetary space resembling that created in the earth's atmosphere by ordinary winds and convection currents. Thus the quasars, which have very small apparent diameters, seem to twinkle like stars. Radio sources of extended diameter such as radio galaxies are immune to interplanetary scintillation in the same way that the larger planets resist atmospheric scintillation. The hypothesis that the solar wind is responsible for the twinkling of quasars is published in *Nature* by A. Hewish, P. F. Scott and D. Wills of Cambridge.

Restrained Vaccinations

Immunization against poliomyelitis with the Sabin live-virus oral vaccine should ordinarily be limited to children, a special advisory committee has recommended to the Public Health Service; vaccination of people over 18 should be undertaken only in epidemic situations, on entry into military service or before foreign travel. Albert B. Sabin, developer of the live-virus vaccine, dissented from the committee report, which involved analysis of 87 cases of "polio-like illness" associated with vaccination in nonepidemic areas since 1961. The committee found that 57 cases were "compatible with the possibility of having been induced by the vaccine"; epidemiological evidence indicated that some of these cases, most of them in adults, were caused by the vaccine. The risk factor is low, however, ranging from one case in 2.5 million vaccinations against Type III poliomyelitis to one in 50 million vaccinations against Type II. There was no apparent association of cases with specific lots of the vaccine.

The advisory committee—made up of virologists, epidemiologists and pediatricians—urged that efforts to immunize children with the oral vaccine be pressed vigorously, particularly in economically depressed populations that have not yet been thoroughly covered. As evidence of the great efficacy of vaccination the committee cited the spectacular decline in the incidence of paralytic poliomyelitis since the introduction of the Salk killed-virus vaccine in 1955: the annual rate fell from 14.6 cases per 100,000 in the period 1950–1954 to 1.8 cases in 1957–1960 and only .2 in 1963.

Subcellular Heredity

A long-standing question in biology as to the formation of certain of the living cell's organelles, or subcellular organs, has been answered tentatively by Aharon Gibor and S. Granick of the Rockefeller Institute. Writing in *Science,* they advance the hypothesis that plastids, which appear in plant cells and function in photosynthesis, and mitochondria, which appear in both plant and animal cells and function in the release of energy, are semiautonomous bodies with their own hereditary systems. Previous hypotheses have suggested that the reproduction of these organelles was controlled by the nucleus of the cell.

As evidence in support of their hypothesis the authors cite several findings and inferences from their work and that of others. One is that plastids and mitochondria contain DNA and RNA, the nucleic-acid constituents of every genetic apparatus. Another is that replication of the DNA occurs in the organelle,

as indicated by the fact that mutations can be produced in plastids by ultraviolet irradiation of the cell while the nucleus is shielded. A third is the indication, gained partly from experiments using radioactive tracers, that plastids and mitochondria are self-duplicating.

Gibor and Granick compared the hereditary properties of plastids in the organism *Euglena* and of mitochondria in yeast, as indicated by mutations induced in both, and found many similarities. "Because of these similarities in two unrelated organisms," they write, "we suggest that a DNA unit that is self-duplicating and that serves as a code for RNA is the basic hereditary unit of each plastid and mitochondrion." They add that "much work must be done if this reasonable hypothesis is to be converted to well-founded theory."

Reflecting on the possible significance of an arrangement in which every cell has numerous organelles each with its own hereditary apparatus, Gibor and Granick suggest two related possibilities. One is that the energy-releasing function of mitochondria and the photosynthesizing function of plastids "are thus maintained inviolate," so that the species is given greater stability. Secondly, "certain mutations could occur independently in each organelle DNA unit, and these mutations could be carried along so that, when drastic environmental changes occurred, there could be selection for the most suitable organelles."

Artificial Gill

A new synthetic membrane, capable of extracting oxygen from ordinary air or from seawater, may provide the basis for a host of applications. The membrane, developed by Walter L. Robb of the General Electric Research Laboratory, is made of silicone rubber and is about a thousandth of an inch thick. Although it is completely free of holes, it permits the passage of certain liquids and gases more easily than others. The molecules of these substances actually go into solution with the material of the membrane on one side and emerge from solution on the other side.

Oxygen, which ordinarily constitutes about 20 percent of the atmosphere, passes through the new membrane more than twice as fast as nitrogen, which is four times as plentiful. Thus if ordinary air is brought into contact with one side of the membrane while the other side is maintained at a lower pressure, the air passing through the mem-

brane will be rich in oxygen. For example, if the low-pressure side of the membrane is maintained at a fifteenth of atmospheric pressure, the air passing through the membrane will contain about 35 percent oxygen. Since patients in hospital oxygen tents normally require enriched air containing about 35 percent oxygen, a few square yards of the new membrane, together with a pump to remove the enriched air from the low-pressure side, could eliminate the need for costly and cumbersome oxygen cylinders.

Another potential application of the new membrane takes advantage of the fact that seawater is saturated with air to a depth of several hundred feet. A membrane with seawater flowing across one side and with the pressure below one atmosphere on the other side would extract oxygen and nitrogen from the water and resist the passage of the water, even under very high pressure. Carbon dioxide and other gases would conveniently pass through the membrane in the opposite direction and be released into the water. Thus the membrane could perform the same functions as the gill of a fish. The small amount of water that would pass through the membrane would be an added bonus: the salt would be removed from it as it passed through the membrane. The crew of a submarine or an underwater experiment station could therefore be supplied not only with air to breathe but also with fresh water for drinking.

Carcinogenic Mold

Students of human nutrition are showing increasing concern over a substance, secreted by tropical and semitropical strains of a common mold, that causes cancer of the liver in a wide variety of laboratory animals, including trout, ducks, mice and rats. The mold, *Aspergillus flavus,* can thrive on cottonseed and corn, but it most commonly attacks the peanut, which is damp when it is harvested from the ground. Any injury to the peanut shell enables the mold to reach the kernel. The secretion of the mold, called aflatoxin, is remarkably stable and is usually unchanged by subsequent processing.

Last year George Buchi, Gerald N. Wogan and their colleagues at the Massachusetts Institute of Technology isolated the toxin. Two British investigators, J. M. Barnes of the Medical Research Council Laboratories and W. H. Butler of University College Hospital, recently reported in *Nature* that pure aflatoxin, when added to the normal diet of laboratory animals, regularly produces tumors of the liver.

Peanut-oil cake is one of the protein additives widely used to bolster deficient diets in underdeveloped countries. Because oil-cake samples from all producing areas have been found to contain aflatoxin, international agencies have now halted the use of the peanut byproduct in diet-improving programs. It has not yet been demonstrated, however, that aflatoxin causes cancer of the liver in man. Studies are now being undertaken to determine whether or not such cancers, which have a varied geographical distribution and a high incidence in parts of Africa and Asia, can be correlated with the consumption of peanuts or peanut products from areas infested with toxin-producing strains of *Aspergillus flavus.*

Food-producing Bubbles

The bubbles made by waves at sea have been found to make a vital contribution to the oceanic food chain. Molecules from the vast supply of organic chemicals dissolved in seawater adhere in large numbers to the air bubbles' two-dimensional boundary layers. In the process they form clumps of organic matter that are eaten by the smallest members of the marine animal population.

The discovery of the new food-producing mechanism resulted from the dissatisfaction of some marine biologists with the traditional view of the pyramid of oceanic life. The phytoplankton (the plant component of the oceans' teeming population of small organisms) was supposed to nourish microscopic species of the zooplankton (the animal component), after which successively larger marine animals preyed on the smaller. The wastes and the dead bodies of both populations were then converted into their constituent chemicals by bacterial action, providing nutrients for more phytoplankton. Gordon A. Riley of Yale University recently called attention to two contradictions in this view. First, many zooplankton thrive and multiply at depths where any plant contribution to the food chain is unlikely. Second, the drop in solar energy during the winter drastically reduces the plant population of the oceans without any apparent effect on the animal population.

Proposing that the zooplankton must have some other initial food source, Riley pointed out that the quantity of organic matter in suspension or in solution in the oceans is at least 50 times greater than that contained in all living plankton. In 1961 and 1962 Riley went on to collect abundant aggregates of nonliving matter from the waters of Long Island Sound.

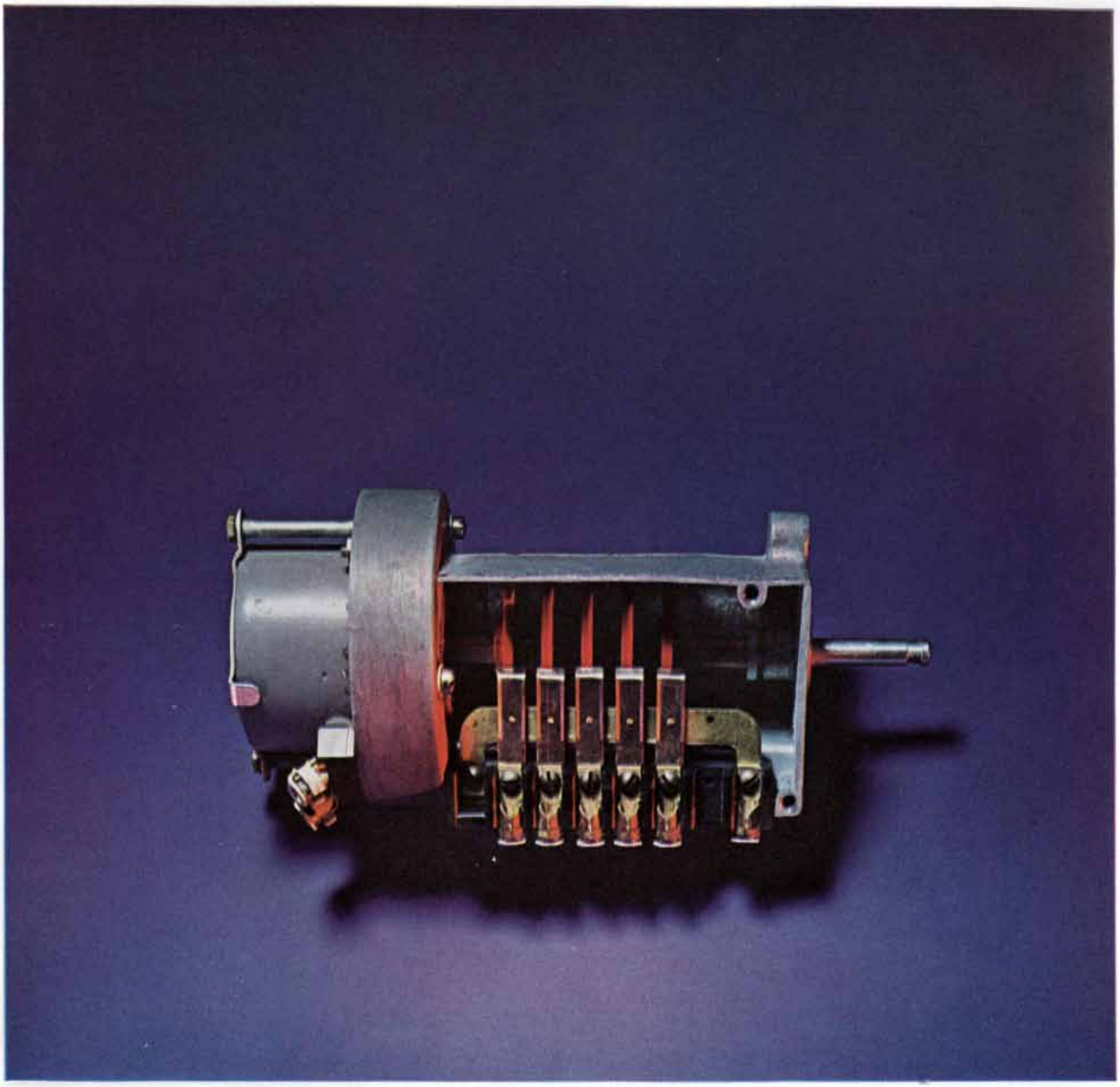
Seeking the means whereby such aggregates were formed, E. R. Baylor and W. H. Sutcliffe of the Woods Hole Oceanographic Institution passed streams of air bubbles through seawater in the laboratory. They found that the bubbles provided surfaces to which molecules in solution could adhere readily and thereby combine into larger particles. The longer and more vigorous the bubbling process was, the larger the particles grew.

Further investigations by Riley have shown that once the organic aggregates have formed they can sink to abyssal depths. For the first 1,500 feet below the surface their abundance diminishes; below that depth it remains constant. In Riley's view these particles not only feed the zooplankton of deep waters but also compose the "marine snow" frequently observed at these depths.

Galactic Radicals

The hydroxyl radical—the combination of a hydrogen atom and an oxygen atom—has been found to be 1,000 times more abundant toward the center of our galaxy than elsewhere in the galaxy. The radical, which emits and absorbs 18-centimeter radio waves, was detected in space last year by radio astronomers at the Massachusetts Institute of Technology. They picked up the radiation as a faint absorption line in the spectrum of the strong radio source Cassiopeia A, which lies toward the rim of the galaxy. Their findings indicated that there was one hydroxyl radical in interstellar space for every 10 million atoms of neutral, or un-ionized, hydrogen.

Since then J. G. Bolton and his colleagues in the Radiophysics Laboratory of the Australian Commonwealth Scientific and Industrial Research Organisation have used the 210-foot radio telescope at Parkes in New South Wales to check the same 18-centimeter band in the spectrum of Sagittarius A, a strong radio source near the galactic center. In this region the Australian investigators have found the surprisingly high ratio of one hydroxyl radical to 10,000 atoms of neutral hydrogen. The distribution of the radical does not, moreover, appear to be random; the radicals are collected in discrete clouds, each with a characteristic velocity. In the case of at least one cloud the direction of motion is toward the galactic center.



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

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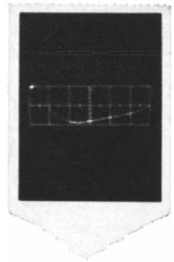

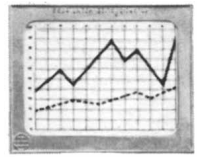

Type 146-L is one of a pair of Polaroid Land films which give you black and white transparencies instead of prints. Within moments after you click the shutter you can project them as lantern slides. This one, rated at A.S.A. 120, is best suited for line work and develops in 10 seconds.

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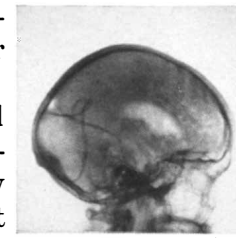

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THE HEMOGLOBIN MOLECULE

Its 10,000 atoms are assembled into four chains, each a helix with several bends. The molecule has one shape when ferrying oxygen molecules and a slightly different shape when it is not

by M. F. Perutz

In 1937, a year after I entered the University of Cambridge as a graduate student, I chose the X-ray analysis of hemoglobin, the oxygen-bearing protein of the blood, as the subject of my research. Fortunately the examiners of my doctoral thesis did not insist on a determination of the structure, otherwise I should have had to remain a graduate student for 23 years. In fact, the complete solution of the problem, down to the location of each atom in this giant molecule, is still outstanding, but the structure has now been mapped in enough detail to reveal the intricate three-dimensional folding of each of its four component chains of amino acid units, and the positions of the four pigment groups that carry the oxygen-combining sites.

The folding of the four chains in hemoglobin turns out to be closely similar to that of the single chain of myoglobin, an oxygen-bearing protein in muscle whose structure has been elucidated in atomic detail by my colleague John C. Kendrew and his collaborators. Correlation of the structure of the two proteins allows us to specify quite accurately, by purely physical methods, where each amino acid unit in hemoglobin lies with respect to the twists and turns of its chains.

Physical methods alone, however, do not yet permit us to decide which of the 20 different kinds of amino acid units occupies any particular site. This knowledge has been supplied by chemical analysis; workers in the U.S. and in Germany have determined the sequence of the 140-odd amino acid units along each of the hemoglobin chains. The combined results of the two different methods of approach now provide an accurate picture of many facets of the hemoglobin molecule.

In its behavior hemoglobin does not resemble an oxygen tank so much as a molecular lung. Two of its four chains shift back and forth, so that the gap between them becomes narrower when oxygen molecules are bound to the hemoglobin, and wider when the oxygen is released. Evidence that the chemical activities of hemoglobin and other proteins are accompanied by structural changes had been discovered before, but this is the first time that the nature of such a change has been directly demonstrated. Hemoglobin's change of shape makes me think of it as a breathing molecule, but paradoxically it expands, not when oxygen is taken up but when it is released.

When I began my postgraduate work in 1936 I was influenced by three inspiring teachers. Sir Frederick Gowland Hopkins, who had received a Nobel prize in 1929 for discovering the growth-stimulating effect of vitamins, drew our attention to the central role played by enzymes in catalyzing chemical reactions in the living cell. The few enzymes isolated at that time had all proved to be proteins. David Keilin, the discoverer of several of the enzymes that catalyze the processes of respiration, told us how the chemical affinities and catalytic properties of iron atoms were altered when the iron combined with different proteins. J. D. Bernal, the X-ray crystallographer, was my research supervisor. He and Dorothy Crowfoot Hodgkin had taken the first X-ray diffraction pictures of crystals of protein a year or two before I arrived, and they had discovered that protein molecules, in spite of their large size, have highly ordered structures. The wealth of sharp X-ray diffraction spots produced by a single crystal of an enzyme such as pepsin could be explained only if every one, or almost every one, of the 5,000 atoms in the pepsin molecule occupied a definite position that was repeated in every one of the myriad of pepsin molecules packed in the crystal. The notion is commonplace now, but it caused a sensation at a time when proteins were still widely regarded as "colloids" of indefinite structure.

In the late 1930's the importance of the nucleic acids had yet to be discovered; according to everything I had learned the "secret of life" appeared to be concealed in the structure of proteins. Of all the methods available in chemistry and physics, X-ray crystallography seemed to offer the only chance, albeit an extremely remote one, of determining that structure.

The number of crystalline proteins then available was probably not more than a dozen, and hemoglobin was an obvious candidate for study because of its supreme physiological importance, its ample supply and the ease with which it could be crystallized. All the same, when I chose the X-ray analysis of hemoglobin as the subject of my Ph.D. thesis, my fellow students regarded me with a pitying smile. The most complex organic substance whose structure had yet been determined by X-ray analysis was the molecule of the dye phthalocyanin, which contains 58 atoms. How could I hope to locate the thousands of atoms in the molecule of hemoglobin?

The Function of Hemoglobin

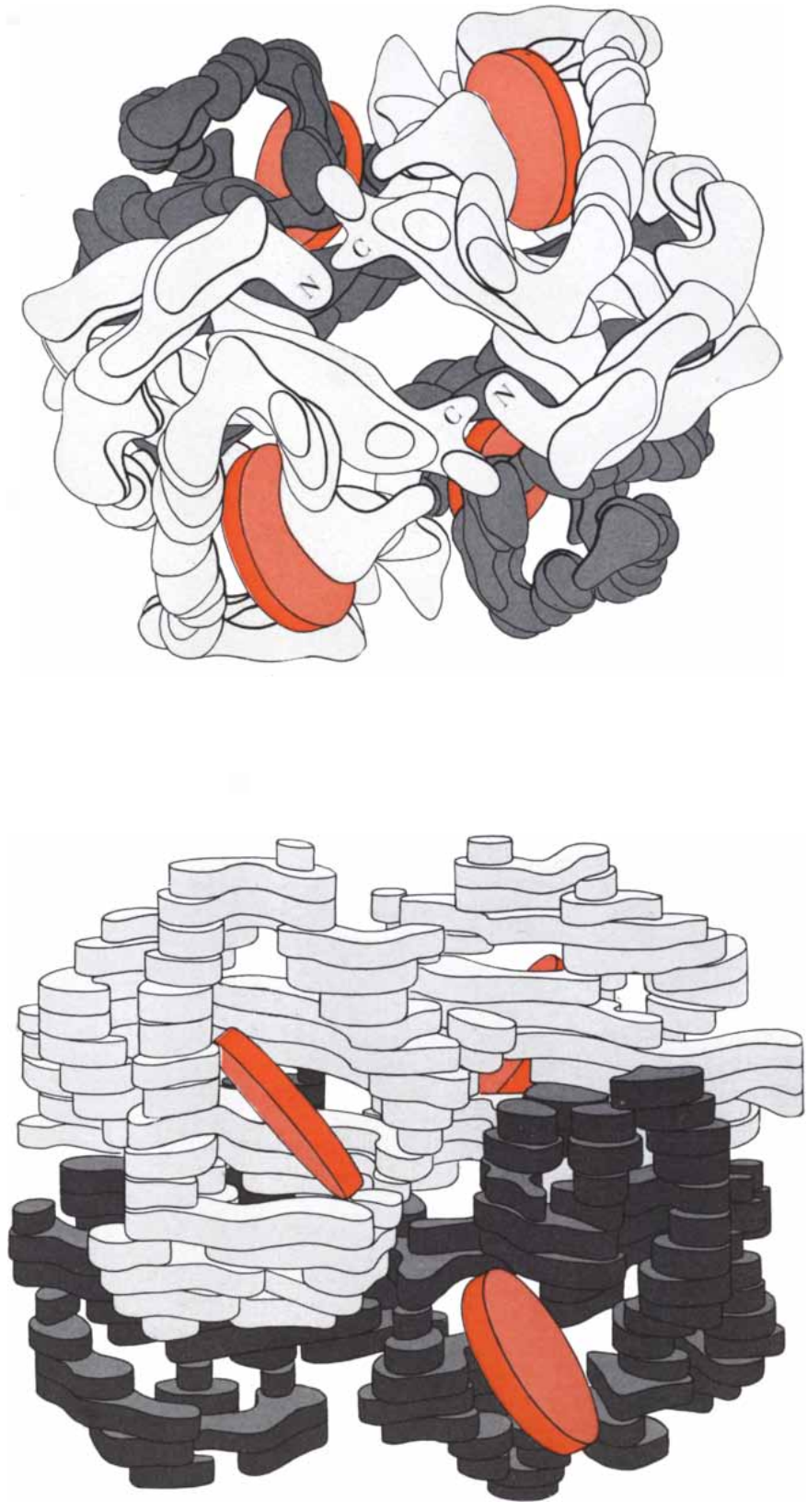
Hemoglobin is the main component of the red blood cells, which carry oxygen from the lungs through the arteries to the tissues and help to carry carbon dioxide through the veins back to the lungs. A single red blood cell contains about 280 million molecules of hemoglobin. Each molecule has 64,500 times the weight of a hydrogen atom and is

made up of about 10,000 atoms of hydrogen, carbon, nitrogen, oxygen and sulfur, plus four atoms of iron, which are more important than all the rest. Each iron atom lies at the center of the group of atoms that form the pigment called heme, which gives blood its red color and its ability to combine with oxygen. Each heme group is enfolded in one of the four chains of amino acid units that collectively constitute the protein part of the molecule, which is called globin. The four chains of globin consist of two identical pairs. The members of one pair are known as alpha chains and those of the other as beta chains. Together the four chains contain a total of 574 amino acid units.

In the absence of an oxygen carrier a liter of arterial blood at body temperature could dissolve and transport no more than three milliliters of oxygen. The presence of hemoglobin increases this quantity 70 times. Without hemoglobin large animals could not get enough oxygen to exist. Similarly, hemoglobin is responsible for carrying more than 90 percent of the carbon dioxide transported by venous blood.

Each of the four atoms of iron in the hemoglobin molecule can take up one molecule (two atoms) of oxygen. The reaction is reversible in the sense that oxygen is taken up where it is plentiful, as in the lungs, and released where it is scarce, as in the tissues. The reaction is accompanied by a change in color: hemoglobin containing oxygen, known as oxyhemoglobin, makes arterial blood look scarlet; reduced, or oxygen-free, hemoglobin makes venous blood look purple. The term "reduced" for the oxygen-free form is really a misnomer because "reduced" means to the chemist that electrons have been added to an atom or a group of atoms. Actually, as James B. Conant of Harvard University demonstrated in 1923, the iron atoms in both reduced hemoglobin and oxyhemoglobin are in the same electronic condition: the divalent, or ferrous, state. They become oxidized to the trivalent, or ferric, state if hemoglobin is treated with a ferricyanide or removed from the red cells and exposed to the air for a considerable time; oxidation also occurs in certain blood diseases. Under these conditions hemoglobin turns brown and is known as methemoglobin, or ferrihemoglobin.

Ferrous iron acquires its capacity for binding molecular oxygen only through its combination with heme and globin. Heme alone will not bind oxygen, but the specific chemical environment of the globin makes the combina-



HEMOGLOBIN MOLECULE, as deduced from X-ray diffraction studies, is shown from above (*top*) and side (*bottom*). The drawings follow the representation scheme used in three-dimensional models built by the author and his co-workers. The irregular blocks represent electron-density patterns at various levels in the hemoglobin molecule. The molecule is built up from four subunits: two identical alpha chains (*light blocks*) and two identical beta chains (*dark blocks*). The letter "N" in the top view identifies the amino ends of the two alpha chains; the letter "C" identifies the carboxyl ends. Each chain enfolds a heme group (*colored disk*), the iron-containing structure that binds oxygen to the molecule.

X-RAY DIFFRACTION PATTERN was made from a single crystal of hemoglobin that was rotated during the photographic exposure. Electrons grouped around the centers of the atoms in the crystal scatter the incident X rays, producing a symmetrical array of spots. Spots that are equidistant from the center and opposite each other have the same density.

tion possible. In association with other proteins, such as those of the enzymes peroxidase and catalase, the same heme group can exhibit quite different chemical characteristics.

The function of the globin, however, goes further. It enables the four iron atoms within each molecule to interact in a physiologically advantageous manner. The combination of any three of the iron atoms with oxygen accelerates the combination with oxygen of the fourth; similarly, the release of oxygen by three of the iron atoms makes the fourth cast off its oxygen faster. By tending to make each hemoglobin molecule carry either four molecules of oxygen or none, this interaction ensures efficient oxygen transport.

I have mentioned that hemoglobin also plays an important part in bearing carbon dioxide from the tissues back to the lungs. This gas is not borne by the iron atoms, and only part of it is bound directly to the globin; most of it is taken up by the red cells and the noncellular fluid of the blood in the form of bicarbonate. The transport of bicarbonate is facilitated by the disappearance of an acid group from hemoglobin for each molecule of oxygen discharged. The reappearance of the acid group when oxygen is taken up again in the lungs sets in motion a series of chemical reactions that leads to the discharge of carbon dioxide. Conversely, the presence of bicarbonate and lactic acid in the tissues accelerates the liberation of oxygen.

Breathing seems so simple, yet it appears as if this elementary manifestation of life owes its existence to the interplay of many kinds of atoms in a giant molecule of vast complexity. Elucidating the structure of the molecule should tell us not only what the molecule looks like but also how it works.

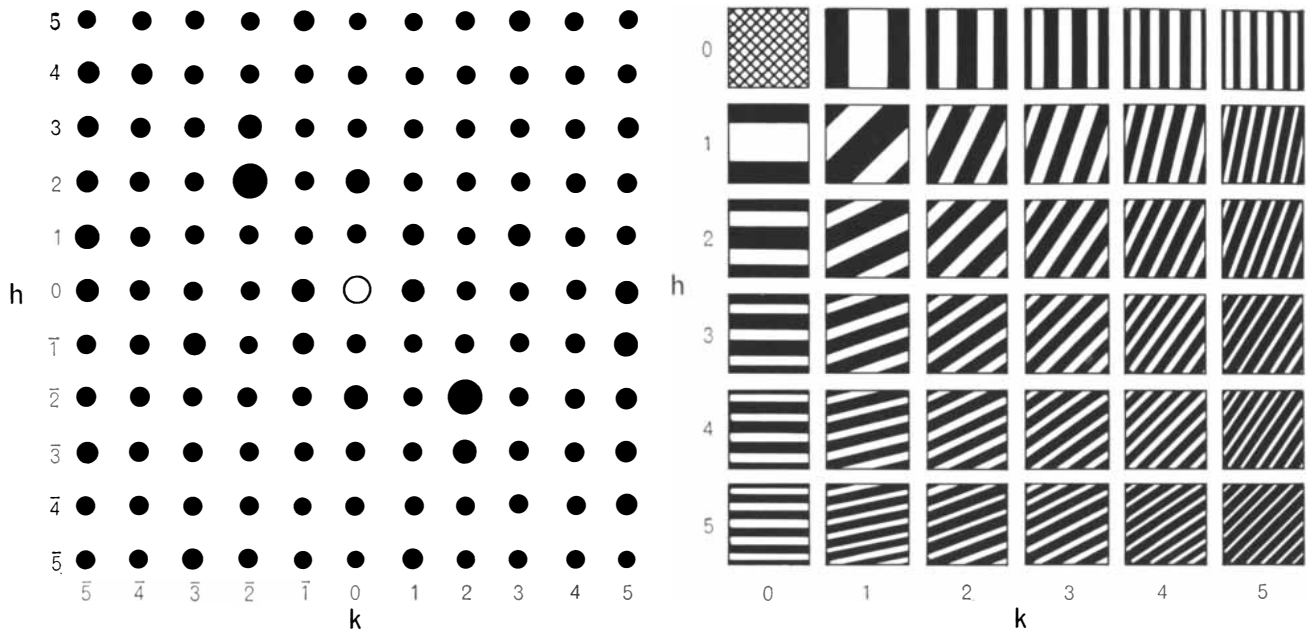
The Principles of X-Ray Analysis

The X-ray study of proteins is sometimes regarded as an abstruse subject comprehensible only to specialists, but the basic ideas underlying our work are so simple that some physicists find them boring. Crystals of hemoglobin and other proteins contain much water and, like living tissues, they tend to lose their regularly ordered structure on drying. To preserve this order during X-ray analysis crystals are mounted wet in small glass capillaries. A single crystal is then illuminated by a narrow beam of X rays that are essentially all of one wavelength. If the crystal is kept stationary, a photographic film placed behind it will often exhibit a pattern of spots lying on ellipses, but if the crystal is rotated in certain ways, the spots can be made to appear at the corners of a regular lattice that is related to the arrangement of the molecules in the crystal [*see illustration at left*]. Moreover, each spot has a characteristic intensity that is determined in part by the arrangement of atoms inside the molecules. The reason for the different intensities is best explained in the words of W. L. Bragg, who founded X-ray analysis in 1913—the year after Max von Laue had discovered that X rays are diffracted by crystals—and who later succeeded Lord Rutherford as Cavendish Professor of Physics at Cambridge:

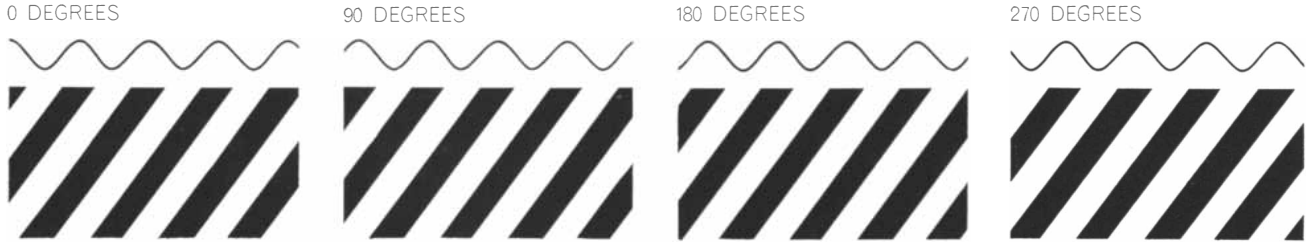
"It is well known that the form of the lines ruled on a [diffraction] grating has an influence on the relative intensity of the spectra which it yields. Some spectra may be enhanced, or reduced, in intensity as compared with others. Indeed, gratings are sometimes ruled in such a way that most of the energy is thrown into those spectra which it is most desirable to examine. The form of the line on the grating does not influence the positions of the spectra, which depend on the number of lines to the centimetre, but the individual lines scatter more light in some directions than others, and this enhances the spectra which lie in those directions.

"The structure of the group of atoms which composes the unit of the crystal grating influences the strength of the various reflexions in exactly the same way. The rays are diffracted by the electrons grouped around the centre of each atom. In some directions the atoms conspire to give a strong scattered beam, in others their effects almost annul each other by interference. The exact arrangement of the atoms is to be deduced by comparing the strength of the reflexions from different faces and in different orders."

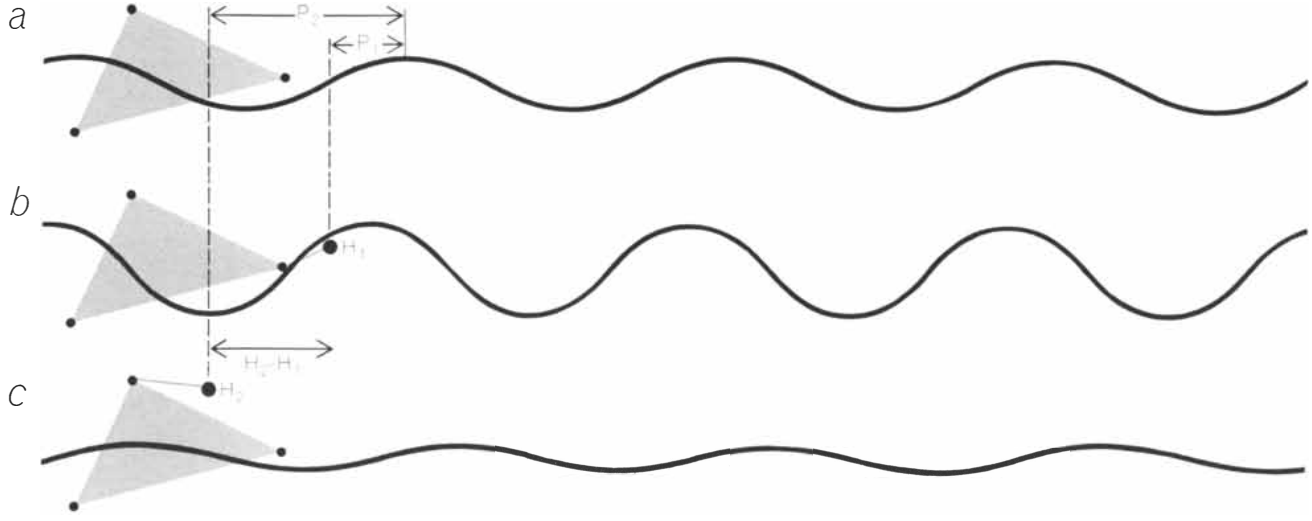
Thus there should be a way of reversing the process of diffraction, of proceeding backward from the diffraction pattern to an image of the arrangement of atoms in the crystal. Such an image can actually be produced, somewhat laboriously, as follows. It will be noted that spots on opposite sides of the center of an X-ray picture have the same



INTERPRETATION OF X-RAY IMAGE can be done with a special optical device to generate a set of diffraction fringes (*right*) from the spots in an X-ray image (*left*). Each pair of symmetrically related spots produces a unique set of fringes. Thus the spots indexed $2,\bar{2}$ and $\bar{2},2$ yield the fringes indexed 2,2. A two-dimensional image of the atomic structure of a crystal can be generated by printing each set of fringes on the same sheet of photographic paper. But the phase problem (*below*) must be solved first.

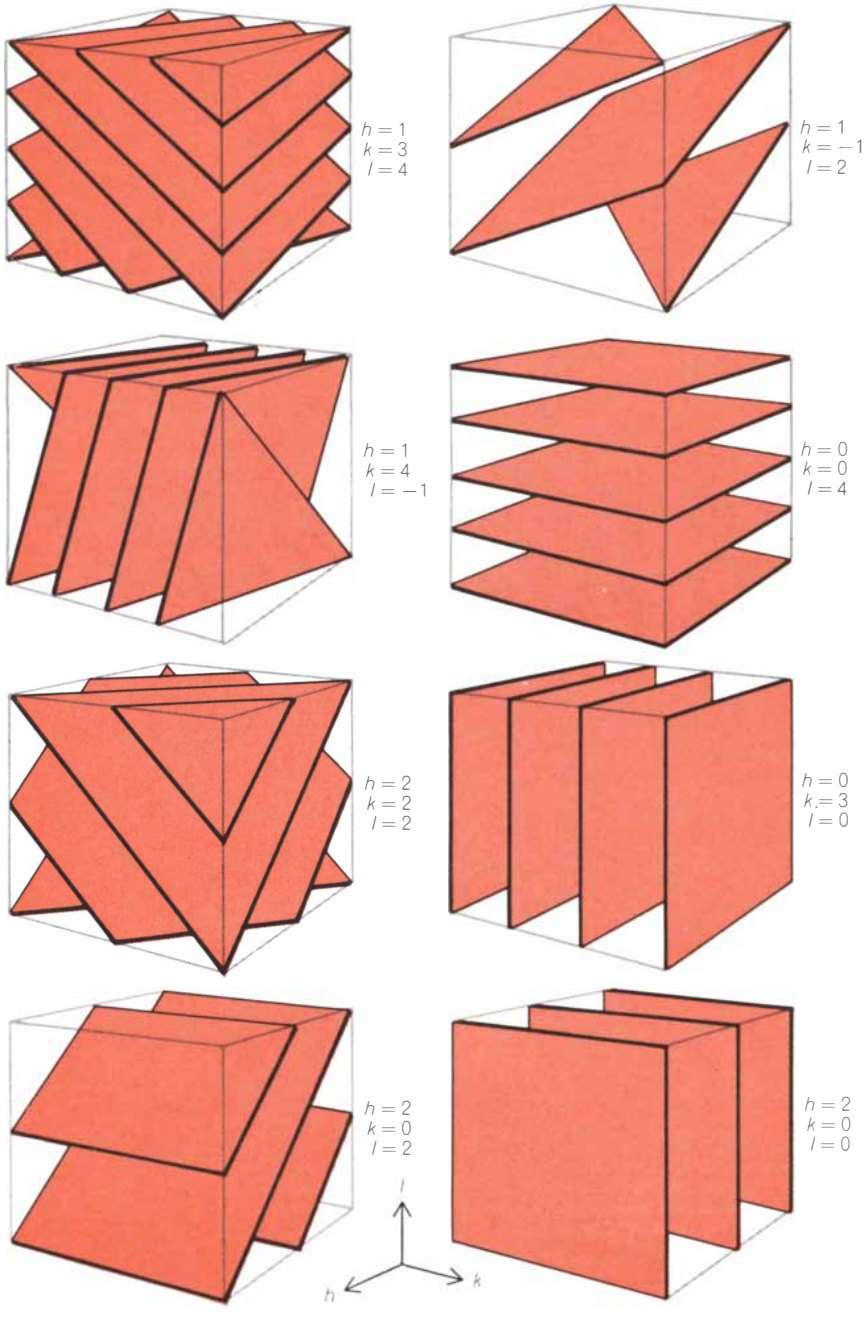


PHASE PROBLEM arises because the spots in an X-ray image do not indicate how the fringes are related in phase to an arbitrarily chosen common origin. Here four identical sets of fringes are related by different phases to the point of origin at the top left corner. The phase marks the distance of the wave crest from the origin, measured in degrees. One wavelength is 360 degrees.



HEAVY-ATOM REPLACEMENT METHOD provides information about phases by changing the intensities of the X-ray diffraction pattern. In *a* a highly oversimplified protein (a triangle of three atoms) scatters a sinusoidal wave that represents the amplitude and phase of a single set of fringes. In *b* and *c*, after heavy atoms H_1 and H_2 are attached to the protein in different positions, the wave is changed in amplitude and phase. The heavy atoms can serve as points of common origin for measuring the magnitude of the phases (P_1 and P_2) of waves scattered by the unaltered protein. The distance between H_1 and H_2 must be accurately known.

degree of intensity. With the aid of a simple optical device each symmetrically related pair of spots can be made to generate a set of diffraction fringes, with an amplitude proportional to the square root of the intensity of the spots. The device, which was invented by Bragg and later developed by H. Lipson and C. A. Taylor at the Manchester College of Science and Technology, consists of a point source of monochromatic light, a pair of plane-convex lenses and a microscope. The pair of spots in the diffraction pattern is represented by a pair of holes in a black mask that is placed between the two lenses. If the point source is placed at the focus of one of the lenses, the waves of parallel light emerging from the two holes will interfere with one another at the focus of the second lens, and their interference pattern, or diffraction pattern, can be observed or photographed through the microscope.



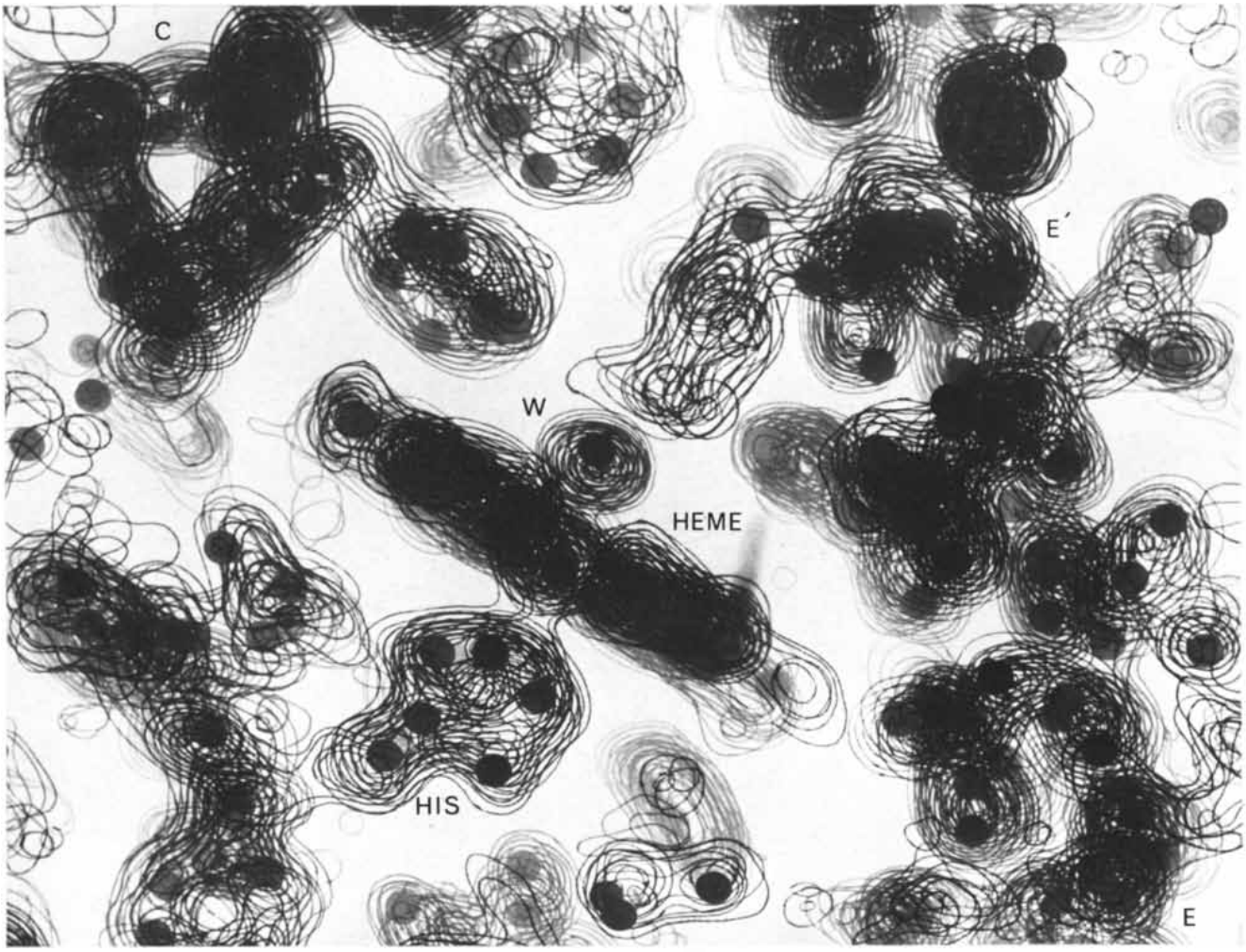
THREE-DIMENSIONAL FRINGES are needed to build up an image of protein molecules. For this purpose many different X-ray diffraction images are prepared and symmetrically related pairs of spots are indexed in three dimensions: h, k and l and $\bar{h}$, $\bar{k}$ and $\bar{l}$. Each pair of spots yields a three-dimensional fringe like those shown here. Fringes from thousands of spots must be superposed in proper phase to build up an image of the molecule.

Imagine that each pair of symmetrically related spots in the X-ray picture is in turn represented by a pair of holes in a mask, and that its diffraction fringes are photographed. Each set of fringes will then be at right angles to the line joining the two holes, and the distance between the fringes will be inversely proportional to the distance between the holes. If the spots are numbered from the center along two mutually perpendicular lines by the indices h and k, the relation between any pair of spots and its corresponding set of fringes would be as shown in the top illustration on the preceding page.

The Phase Problem

An image of the atomic structure of the crystal can be generated by printing each set of fringes in turn on the same sheet of photographic paper, or by superposing all the fringes and making a print of the light transmitted through them. At this point, however, a fatal complication arises. In order to obtain the right image one would have to place each set of fringes correctly with respect to some arbitrarily chosen common origin [*see middle illustration on preceding page*]. At this origin the amplitude of any particular set of fringes may show a crest or trough or some intermediate value. The distance of the wave crest from the origin is called the phase. It is almost true to say that by superposing sets of fringes of given amplitude one can generate an infinite number of different images, depending on the choice of phase for each set of fringes. By itself the X-ray picture tells us only about the amplitudes and nothing about the phases of the fringes to be generated by each pair of spots, which means that half the information needed for the production of the image is missing.

The missing information makes the diffraction pattern of a crystal like a hieroglyphic without a key. Having spent years hopefully measuring the intensities of several thousand spots in the diffraction pattern of hemoglobin, I found myself in the tantalizing position of an explorer with a collection of tablets engraved in an unknown script. For some time Bragg and I tried to develop methods for deciphering the phases, but with only limited success. The solution finally came in 1953, when I discovered that a method that had been developed by crystallographers for solving the phase problem in simpler structures could also be applied to proteins.



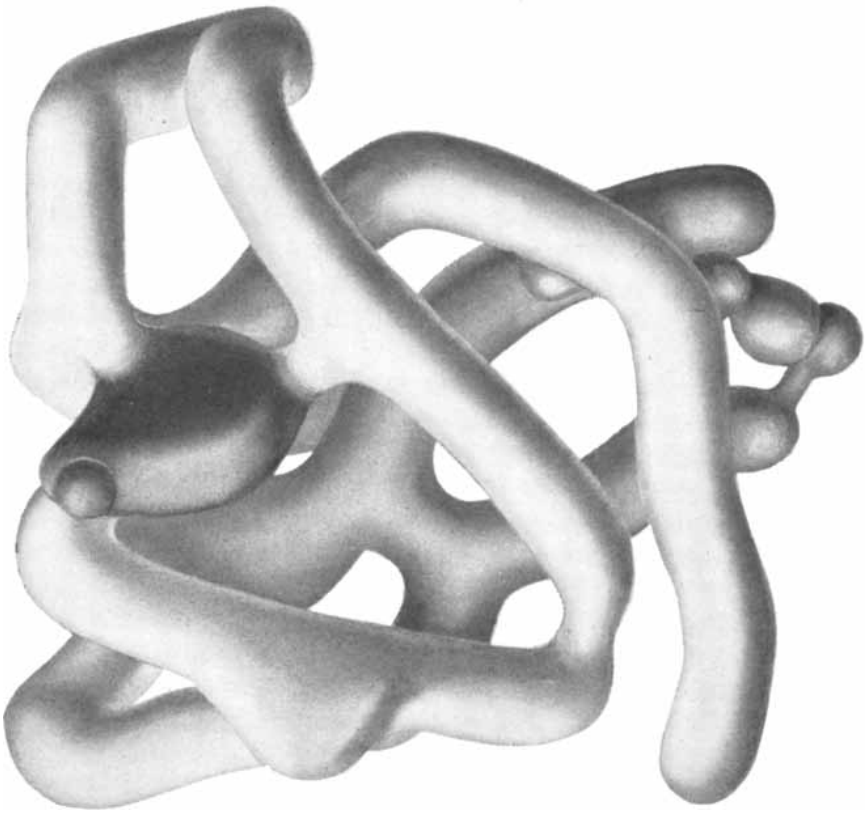
CONTOUR MAPS, drawn on stacked sheets of clear plastic, show a portion of the myoglobin molecule as revealed by superposition of three-dimensional fringe patterns. The maps were made by John C. Kendrew and his associates at the University of Cambridge. Myoglobin is very similar to the beta chain of hemoglobin. The heme group is seen edge on. *His* is an amino acid subunit of histidine that is attached to the iron atom of the heme group. *W* is a water molecule linked to the iron atom. The region between *E* and *E′* represents amino acid subunits arranged in an alpha helix. *C* is an alpha helix seen end on. The black dots mark atomic positions.

In this method the molecule of the compound under study is modified slightly by attaching heavy atoms such as those of mercury to definite positions in its structure. The presence of a heavy atom produces marked changes in the intensities of the diffraction pattern, and this makes it possible to gather information about the phases. From the difference in amplitude in the absence or presence of a heavy atom, the distance of the wave crest from the heavy atom can be determined for each set of fringes. Thus with the heavy atom serving as a common origin the magnitude of the phase can be measured. The bottom illustration on page 67 shows how the phase of a single set of fringes, represented by a sinusoidal wave that is supposedly scattered by the oversimplified protein molecule, can be measured from the increase in amplitude produced by the heavy atom H_1.

Unfortunately this still leaves an ambiguity of sign; the experiment does not tell us whether the phase is to be measured from the heavy atom in the forward or the backward direction. If n is the number of diffracted spots, an ambiguity of sign in each set of fringes would lead to 2^n alternative images of the structure. The Dutch crystallographer J. M. Bijvoet had pointed out some years earlier in another context that the ambiguity could be resolved by examining the diffraction pattern from a second heavy-atom compound.

The bottom illustration on page 67 shows that the heavy atom H_2, which is attached to the protein in a position different from that of H_1, diminishes the amplitude of the wave scattered by the protein. The degree of attenuation allows us to measure the distance of the wave crest from H_2. It can now be seen that the wave crest must be in front of H_1; otherwise its distance from H_1 could not be reconciled with its distance from H_2. The final answer depends on knowing the length and direction of the line joining H_2 to H_1. These quantities are best calculated by a method that does not easily lend itself to exposition in nonmathematical language. It was devised by my colleague Michael G. Rossmann.

The heavy-atom method can be applied to hemoglobin by attaching mercury atoms to the sulfur atoms of the amino acid cysteine. The method works, however, only if this attachment leaves the structure of the hemoglobin molecules and their arrangement in the crystal unaltered. When I first tried it, I was not at all sure that these stringent demands would be fulfilled, and as I developed my first X-ray photograph of mercury hemoglobin my mood alternated between sanguine hopes of immediate success and desperate forebodings of all the possible causes of failure. When the diffraction spots ap-



MYOGLOBIN MOLECULE, as first reconstructed at low resolution by Kendrew and his co-workers in 1957, had this rather repulsive visceral appearance. The sausage-like knot marks the path of the amino acid chain of the molecule. The dark disklike shape (here placed at an incorrect angle) is the heme group. A more detailed and more correct view of myoglobin, as seen from the other side, appears at bottom right on the opposite page.

peared in exactly the same position as in the mercury-free protein but with slightly altered intensities, just as I had hoped, I rushed off to Bragg's room in jubilant excitement, expecting that the structure of hemoglobin and of many other proteins would soon be determined. Bragg shared my excitement, and luckily neither of us anticipated the formidable technical difficulties that were to hold us up for another five years.

Resolution of the Image

Having solved the phase problem, at least in principle, we were confronted with the task of building up a structural image from our X-ray data. In simpler structures atomic positions can often be found from representations of the structure projected on two mutually perpendicular planes, but in proteins a three-dimensional image is essential. This can be attained by making use of the three-dimensional nature of the diffraction pattern. The X-ray diffraction pattern on page 66 can be regarded as a section through a sphere that is filled with layer after layer of diffraction spots. Each pair of spots can be made to generate a set of three-dimensional fringes like the ones shown on page 68. When their phases have been measured, they can be superposed by calculation to build up a three-dimensional image of the protein. The final image is represented by a series of sections through the molecule, rather like a set of microtome sections through a piece of tissue, only on a scale 1,000 times smaller [*see illustration on preceding page*].

The resolution of the image is roughly equal to the shortest wavelength of the fringes used in building it up. This means that the resolution increases with the number of diffracted spots included in the calculation. If the image is built up from part of the diffraction pattern only, the resolution is impaired.

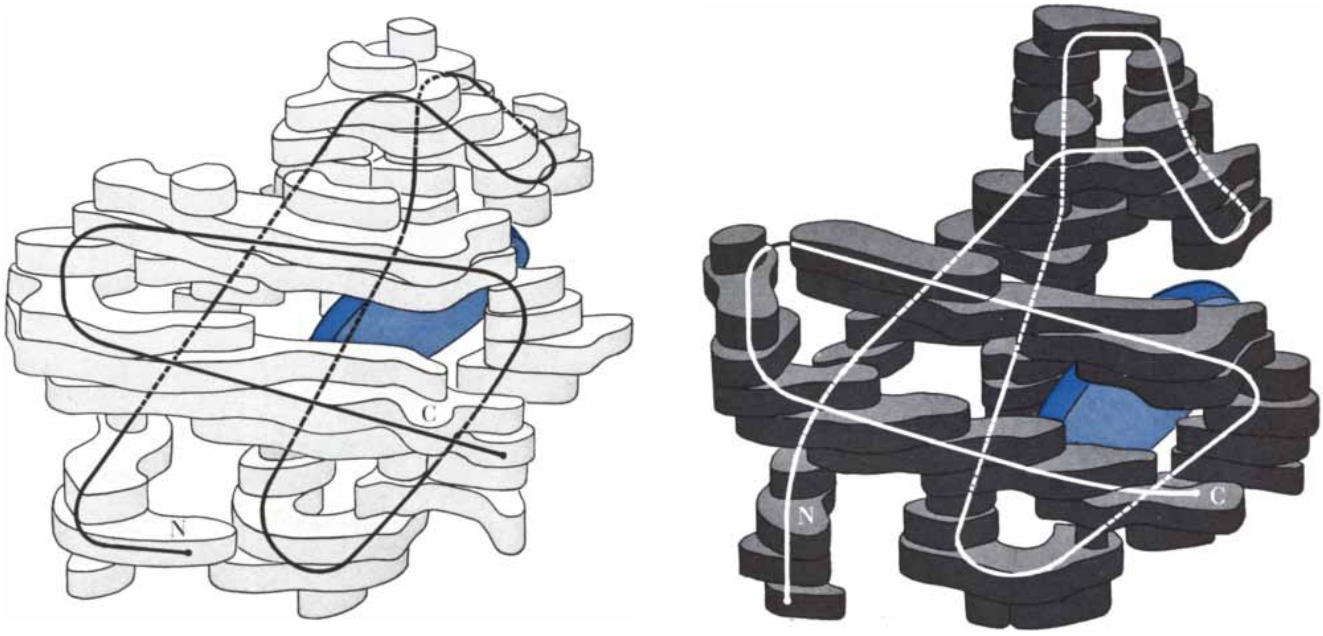
In the X-ray diffraction patterns of protein crystals the number of spots runs into tens of thousands. In order to determine the phase of each spot accurately, its intensity (or blackness) must be measured accurately several times over: in the diffraction pattern from a crystal of the pure protein and in the patterns from crystals of several compounds of the protein, each with heavy atoms attached to different positions in the molecule. Then the results have to be corrected by various geometric factors before they are finally used to build up an image through the superposition of tens of thousands of fringes. In the final calculation tens of millions of numbers may have to be added or subtracted. Such a task would have been quite impossible before the advent of high-speed computers, and we have been fortunate in that the development of computers has kept pace with the expanding needs of our X-ray analyses.

While I battled with technical difficulties of various sorts, my colleague John Kendrew successfully applied the heavy-atom method to myoglobin, a protein closely related to hemoglobin [see "The Three-dimensional Structure of a Protein Molecule," by John C. Kendrew; SCIENTIFIC AMERICAN, December, 1961]. Myoglobin is simpler than hemoglobin because it consists of only one chain of amino acid units and one heme group, which binds a single molecule of oxygen. The complex interaction phenomena involved in hemoglobin's dual function as a carrier of oxygen and of carbon dioxide do not occur in myoglobin, which acts simply as an oxygen store.

Together with Howard M. Dintzis and G. Bodo, Kendrew was brilliantly successful in managing to prepare as many as five different crystalline heavy-atom compounds of myoglobin, which meant that the phases of the diffraction spots could be established very accurately. He also pioneered the use of high-speed computers in X-ray analysis. In 1957 he and his colleagues obtained the first three-dimensional representation of myoglobin [*see illustration on this page*].

It was a triumph, and yet it brought a tinge of disappointment. Could the search for ultimate truth really have revealed so hideous and visceral-looking an object? Was the nugget of gold a lump of lead? Fortunately, like many other things in nature, myoglobin gains in beauty the closer you look at it. As Kendrew and his colleagues increased the resolution of their X-ray analysis in the years that followed, some of the intrinsic reasons for the molecule's strange shape began to reveal themselves. This shape was found to be not a freak but a fundamental pattern of nature, probably common to myoglobins and hemoglobins throughout the vertebrate kingdom.

In the summer of 1959, nearly 22 years after I had taken the first X-ray



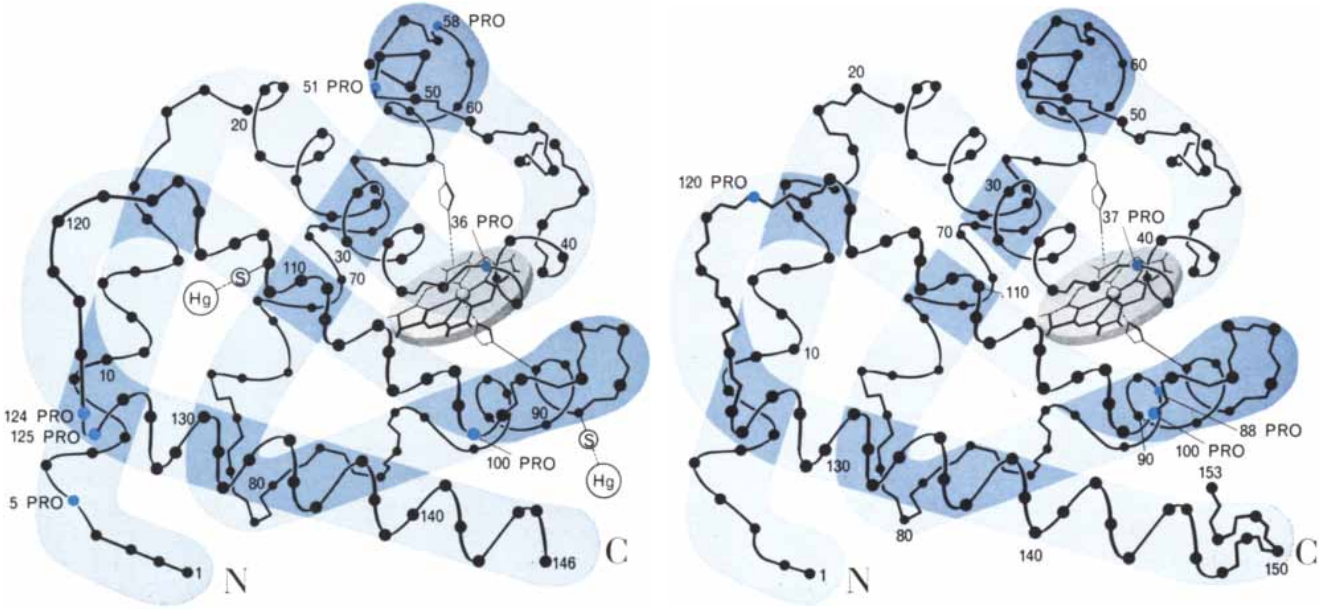
HEMOGLOBIN CHAINS, alpha at left and beta at right, are redrawn from models built by the author and his colleagues. The superposed lines show the course of the central chain. A heme group (*color*) is partly visible, tucked in the back of each model.

pictures of hemoglobin, its structure emerged at last. Michael Rossmann, Ann F. Cullis, Hilary Muirhead, Tony C. T. North and I were able to prepare a three-dimensional electron-density map of hemoglobin at a resolution of 5.5 angstrom units, about the same as that obtained for the first structure of myoglobin two years earlier. This resolution is sufficient to reveal the shape of the chain forming the backbone of a protein molecule but not to show the position of individual amino acids.

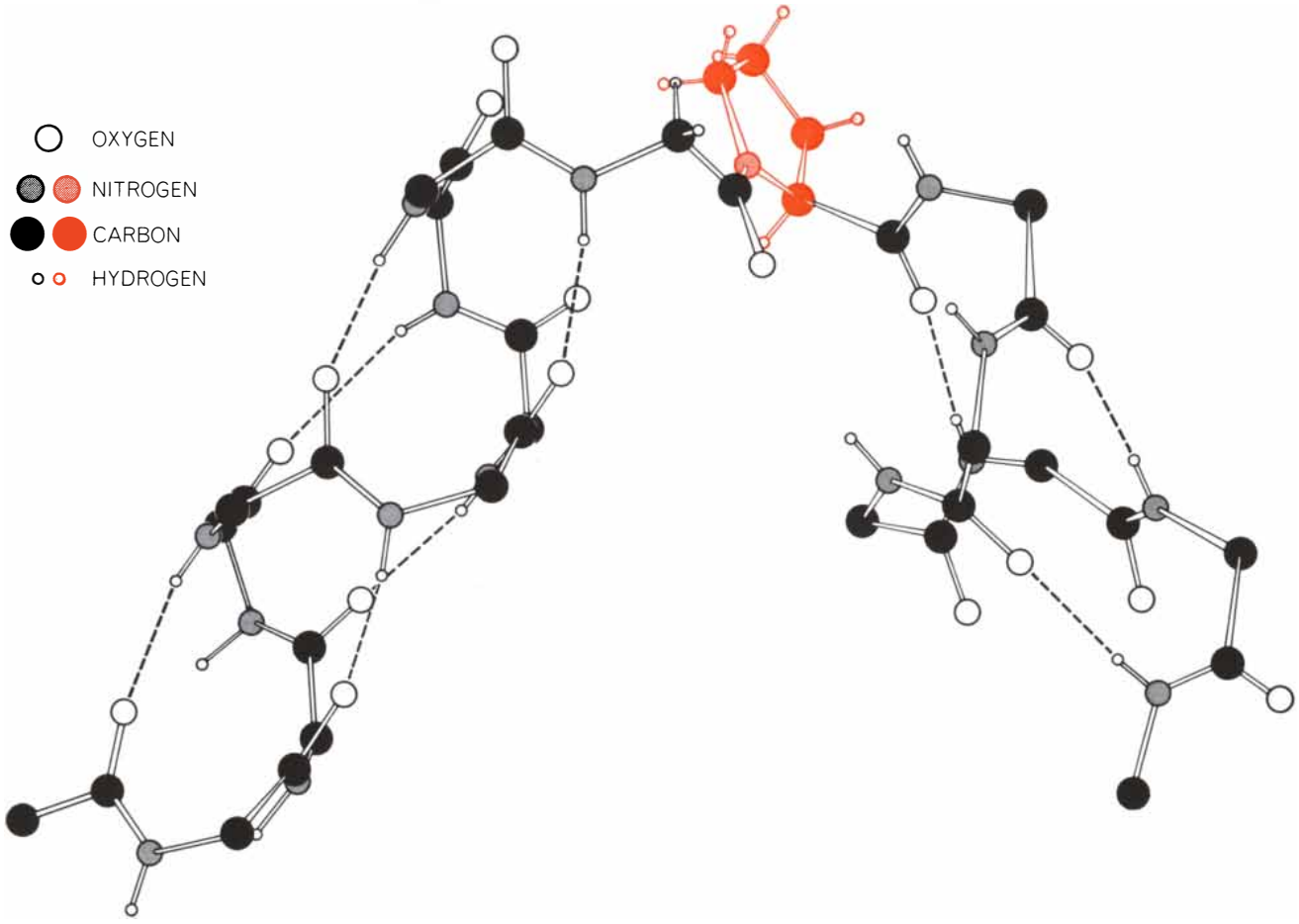
As soon as the numbers printed by the computer had been plotted on contour maps we realized that each of the four chains of hemoglobin had a shape closely resembling that of the single chain of myoglobin. The beta chain and myoglobin look like identical twins, and the alpha chains differ from them merely by a shortcut across one small loop [*see illustration below*].

Kendrew's myoglobin had been extracted from the muscle of the sperm whale; the hemoglobin we used came from the blood of horses. More recent observations indicate that the myoglobins of the seal and the horse, and the hemoglobins of man and cattle, all have the same structure. It seems as though the apparently haphazard and irregular folding of the chain is a pattern specifically devised for holding a heme group in place and for enabling it to carry oxygen.

What is it that makes the chain take up this strange configuration? The extension of Kendrew's analysis to a high-



BETA CHAIN AND MYOGLOBIN appear at left and right. Every 10th amino acid subunit is marked, as are proline subunits (*color*), which often coincide with turns in the chain. Balls marked "Hg" show where mercury atoms can be attached to sulfur atoms (*S*).



CORNER IN HEMOGLOBIN MOLECULE occurs where a subunit of the amino acid proline (*color*) falls between two helical regions in the beta chain. The chain is shown bare; all hydrogen atoms and amino acid side branches, except for proline, are removed.

er resolution shows that the chain of myoglobin consists of a succession of helical segments interrupted by corners and irregular regions. The helical segments have the geometry of the alpha helix predicted in 1951 by Linus Pauling and Robert B. Corey of the California Institute of Technology. The heme group lies embedded in a fold of the chain, so that only its two acid groups protrude at the surface and are in contact with the surrounding water. Its iron atom is linked to a nitrogen atom of the amino acid histidine.

I have recently built models of the alpha and beta chains of hemoglobin and found that they follow an atomic pattern very similar to that of myoglobin. If two protein chains look the same, one would expect them to have much the same composition. In the language of protein chemistry this implies that in the myoglobins and hemoglobins of all vertebrates the 20 different kinds of amino acid should be present in about the same proportion and arranged in similar sequence.

Enough chemical analyses have been done by now to test whether or not this is true. Starting at the Rockefeller Institute and continuing in our laboratory, Allen B. Edmundson has determined the sequence of amino acid units in the molecule of sperm-whale myoglobin. The sequences of the alpha and beta chains of adult human hemoglobin have been analyzed independently by Gerhardt Braunitzer and his colleagues at the Max Planck Institute for Biochemistry in Munich, and by William H. Konigsberg, Robert J. Hill and their associates at the Rockefeller Institute. Fetal hemoglobin, a variant of the human adult form, contains a chain known as gamma, which is closely related to the beta chain. Its complete sequence has been analyzed by Walter A. Schroeder and his colleagues at the California Institute of Technology. The sequences of several other species of hemoglobin and that of human myoglobin have been partially elucidated.

The sequence of amino acid units in proteins is genetically determined, and changes arise as a result of mutation. Sickle-cell anemia, for instance, is an inherited disease due to a mutation in one of the hemoglobin genes. The mutation causes the replacement of a single amino acid unit in each of the beta chains. (The glutamic acid unit normally present at position No. 6 is replaced by a valine unit.) On the molecular scale evolution is thought to involve a succession of such mutations, altering the structure of protein molecules one amino acid unit at a time. Consequently when the hemoglobins of different species are compared, we should expect the sequences in man and apes, which are close together on the evolutionary scale, to be very similar, and those of mammals and fishes, say, to differ more widely. Broadly speaking, this is what is found. What was quite unexpected was the degree of chemical diversity among the amino acid sequences of proteins of similar three-dimensional structure and closely related function. Comparison of the known hemoglobin and myoglobin sequences shows only 15 positions—no more than one in 10—where the same amino acid unit is present in all species. In all the other positions one or more replacements have occurred in the course of evolution.

What mechanism makes these diverse

chains fold up in exactly the same way? Does a template force them to take up this configuration, like a mold that forces a car body into shape? Apart from the topological improbability of such a template, all the genetic and physicochemical evidence speaks against it, suggesting instead that the chain folds up spontaneously to assume one specific structure as the most stable of all possible alternatives.

Possible Folding Mechanisms

What is it, then, that makes one particular configuration more stable than all others? The only generalization to emerge so far, mainly from the work of Kendrew, Herman C. Watson and myself, concerns the distribution of the so-called polar and nonpolar amino acid units between the surface and the interior of the molecule.

Some of the amino acids, such as glutamic acid and lysine, have side groups of atoms with positive or negative electric charge, which strongly attract the surrounding water. Amino acid side groups such as glutamine or tyrosine, although electrically neutral as a whole, contain atoms of nitrogen or oxygen in which positive and negative charges are sufficiently separated to form dipoles; these also attract water, but not so strongly as the charged groups do. The attraction is due to a separation of charges in the water molecule itself, making it dipolar. By attaching themselves to electrically charged groups, or to other dipolar groups, the water molecules minimize the strength of the electric fields surrounding these groups and stabilize the entire structure by lowering the quantity known as free energy.

The side groups of amino acids such as leucine and phenylalanine, on the other hand, consist only of carbon and hydrogen atoms. Being electrically neutral and only very weakly dipolar, these groups repel water as wax does. The reason for the repulsion is strange and intriguing. Such hydrocarbon groups, as they are called, tend to disturb the haphazard arrangement of the liquid water molecules around them, making it ordered as it is in ice. The increase in order makes the system less stable; in physical terms it leads to a reduction of the quantity known as entropy, which is the measure of the disorder in a system. Thus it is the water molecules' anarchic distaste for the orderly regimentation imposed on them by the hydrocarbon side groups that forces these side groups to turn away from water and to stick to one another.

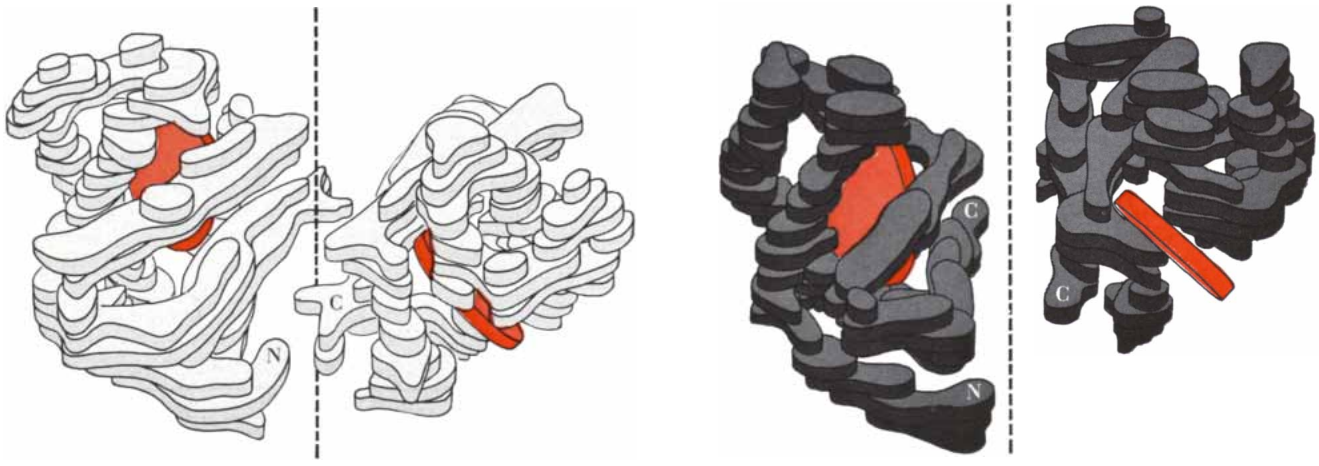
Our models have taught us that most electrically charged or dipolar side groups lie at the surface of the protein molecule, in contact with water. Nonpolar side groups, in general, are either confined to the interior of the molecule or so wedged into crevices on its surface as to have the least contact with water. In the language of physics, the distribution of side groups is of the kind leading to the lowest free energy and the highest entropy of the protein molecules and the water around them. (There is a reduction of entropy due to the orderly folding of the protein chain itself, which makes the system less stable, but this is balanced, at moderate temperatures, by the stabilizing contributions of the other effects just described.) It is too early to say whether these are the only generalizations to be made about the forces that stabilize one particular configuration of the protein chain in preference to all others.

At least one amino acid is known to be a misfit in an alpha helix, forcing the chain to turn a corner wherever the unit occurs. This is proline [*see illustration on opposite page*]. There is, however, only one corner in all the hemoglobins and myoglobins where a proline is always found in the same position: position No. 36 in the beta chain and No. 37 in the myoglobin chain [*see bottom illustration on page 71*]. At other corners the appearance of prolines is haphazard and changes from species to species. Elkan R. Blout of the Harvard Medical School finds that certain amino acids such as valine or threonine, if present in large numbers, inhibit the formation of alpha helices, but these do not seem to have a decisive influence in myoglobin and hemoglobin.

Since it is easier to determine the sequence of amino acid units in proteins than to unravel their three-dimensional structure by X rays, it would be useful to be able to predict the structure from the sequence. In principle enough is probably known about the forces between atoms and about the way they tend to arrange themselves to make such predictions feasible. In practice the enormous number of different ways in which a long chain can be twisted still makes the problem one of baffling complexity.

Assembling the Four Chains

If hemoglobin consisted of four identical chains, a crystallographer would expect them to lie at the corners of a regular tetrahedron. In such an arrangement each chain can be brought into congruence with any of its three neighbors by a rotation of 180 degrees about one of three mutually perpendicular



FOUR CHAINS OF HEMOGLOBIN are arranged in symmetrical fashion. Two alpha chains (*left*) and two beta chains (*right*) face each other across an axis of symmetry (*broken vertical lines*). In the assembled molecule the two alpha chains are inverted over the two beta chains and nested down between them. When arranged in this manner, the four chains lie at the corners of a tetrahedron.

axes of symmetry. Since the alpha and beta chains are chemically different, such perfect symmetry is unattainable, but the actual arrangement comes very close to it. As a first step in the assembly of the molecule two alpha chains are placed near a twofold symmetry axis, so that a rotation of 180 degrees brings one chain into congruence with its partner [*see illustration on preceding page*].

Next the same is done with the two beta chains. One pair, say the alpha chains, is then inverted and placed over the top of the other pair so that the four chains lie at the corners of a tetrahedron. A true twofold symmetry axis now passes vertically through the molecule, and "pseudo-axes" in two directions perpendicular to the first relate the alpha to the beta chains. Thus the arrangement is tetrahedral, but because of the chemical differences between the alpha and beta chains the tetrahedron is not quite regular.

The result is an almost spherical molecule whose exact dimensions are $64 \times 55 \times 50$ angstrom units. It is astonishing to find that four objects as irregular as the alpha and beta chains can fit together so neatly. On formal grounds one would expect a hole to pass through the center of the molecule because chains of amino acid units, being asymmetrical, cannot cross any symmetry axis. Such a hole is in fact found [*see top illustration on page 65*].

The most unexpected feature of the oxyhemoglobin molecule is the way the four heme groups are arranged. On the basis of their chemical interaction one would have expected them to lie close together. Instead each heme group lies in a separate pocket on the surface of the molecule, apparently unaware of the existence of its partners. Seen at the present resolution, therefore, the structure fails to explain one of the most important physiological properties of hemoglobin.

In 1937 Felix Haurowitz, then at the German University of Prague, discovered an important clue to the molecular explanation of hemoglobin's physiological action. He put a suspension of needle-shaped oxyhemoglobin crystals away in the refrigerator. When he took the suspension out some weeks later, the oxygen had been used up by bacterial infection and the scarlet needles had been replaced by hexagonal plates of purple reduced hemoglobin. While Haurowitz observed the crystals under the microscope, oxygen penetrated between the slide and the cover slip, causing the purple plates to dissolve and the scarlet needles of hemoglobin to re-form. This transformation convinced Haurowitz that the reaction of hemoglobin with oxygen must be accompanied by a change in the structure of the hemoglobin molecule. In myoglobin, on the other hand, no evidence for such a change has been detected.

Haurowitz' observation and the enigma posed by the structure of oxyhemoglobin caused me to persuade a graduate student, Hilary Muirhead, to attempt an X-ray analysis at low resolution of the reduced form. For technical reasons human rather than horse hemoglobin was used at first, but we have now found that the reduced hemoglobins of man and the horse have very similar structures, so that the species does not matter here.

Unlike me, Miss Muirhead succeeded in solving the structure of her protein in time for her Ph.D. thesis. When we examined her first electron-density maps, we looked for two kinds of structural change: alterations in the folding of the individual chains and displacements of the chains with respect to each other. We could detect no changes in folding large enough to be sure that they were not due to experimental error. We did discover, however, that a striking displacement of the beta chains had taken place. The gap between them had widened and they had been shifted sideways, increasing the distance between their respective iron atoms from 33.4 to 40.3 angstrom units [*see illustration on page 76*]. The arrangement of the two alpha chains had remained unaltered, as far as we could judge, and the distance between the iron atoms in the beta chains and their nearest neighbors in the alpha chains had also remained the same. It looked as though the two beta chains had slid apart, losing contact with each other and somewhat changing their points of contact with the alpha chains.

F. J. W. Roughton and others at the University of Cambridge suggest that the change to the oxygenated form of

RESIDUE NUMBER	HEMOGLOBIN			MYOGLOBIN
	ALPHA	BETA	GAMMA	
81	MET	LEU	LEU	HIS
82	PRO	LYS	LYS	GLU
83	ASN	GLY	GLY	ALA
84	ALA	THR	THR	GLU
85	LEU	PHE	PHE	LEU
86	SER	ALA	ALA	LYS
87	ALA	THR	GLN	PRO
88	LEU	LEU	LEU	LEU
89	SER	SER	SER	ALA
90	ASP	GLU	GLU	GLN
91	LEU	LEU	LEU	SER
92	HIS	HIS	HIS	HIS
93	ALA	CYS	CYS	ALA
94	HIS	ASP	ASN	THR
95	LYS	LYS	LYS	LYS
96	LEU	LEU	LEU	HIS
97	ARG	HIS	HIS	LYS
98	VAL	VAL	VAL	ILEU
99	ASP	ASP	ASP	PRO
100	PRO	PRO	PRO	ILEU
101	VAL	GLU	GLU	LYS
102	ASP	ASN	ASN	TYR

ALA ALANINE
ARG ARGININE
ASN ASPARAGINE
ASP ASPARTIC ACID
CYS CYSTEINE
GLN GLUTAMINE
GLU GLUTAMIC ACID
GLY GLYCINE
HIS HISTIDINE
ILEU ISOLEUCINE
LEU LEUCINE
LYS LYSINE
MET METHIONINE
PHE PHENYLALANINE
PRO PROLINE
SER SERINE
THR THREONINE
TYR TYROSINE
VAL VALINE

AMINO ACID SEQUENCES are shown for corresponding stretches of the alpha and beta chains of hemoglobin from human adults, the gamma chain that replaces the beta chain in fetal human hemoglobin and sperm-whale myoglobin. Colored bars show where the same amino acid units are found either in all four chains or in the first three. Site numbers for the alpha chain and myoglobin are adjusted slightly because they contain a different number of amino acid subunits overall than do the beta and gamma chains. Over their full length of more than 140 subunits the four chains have only 20 amino acid subunits in common.

hemoglobin takes place after three of the four iron atoms have combined with oxygen. When the change has occurred, the rate of combination of the fourth iron atom with oxygen is speeded up several hundred times. Nothing is known as yet about the atomic mechanism that sets off the displacement of the beta chains, but there is one interesting observation that allows us at least to be sure that the interaction of the iron atoms and the change of structure do not take place unless alpha and beta chains are both present.

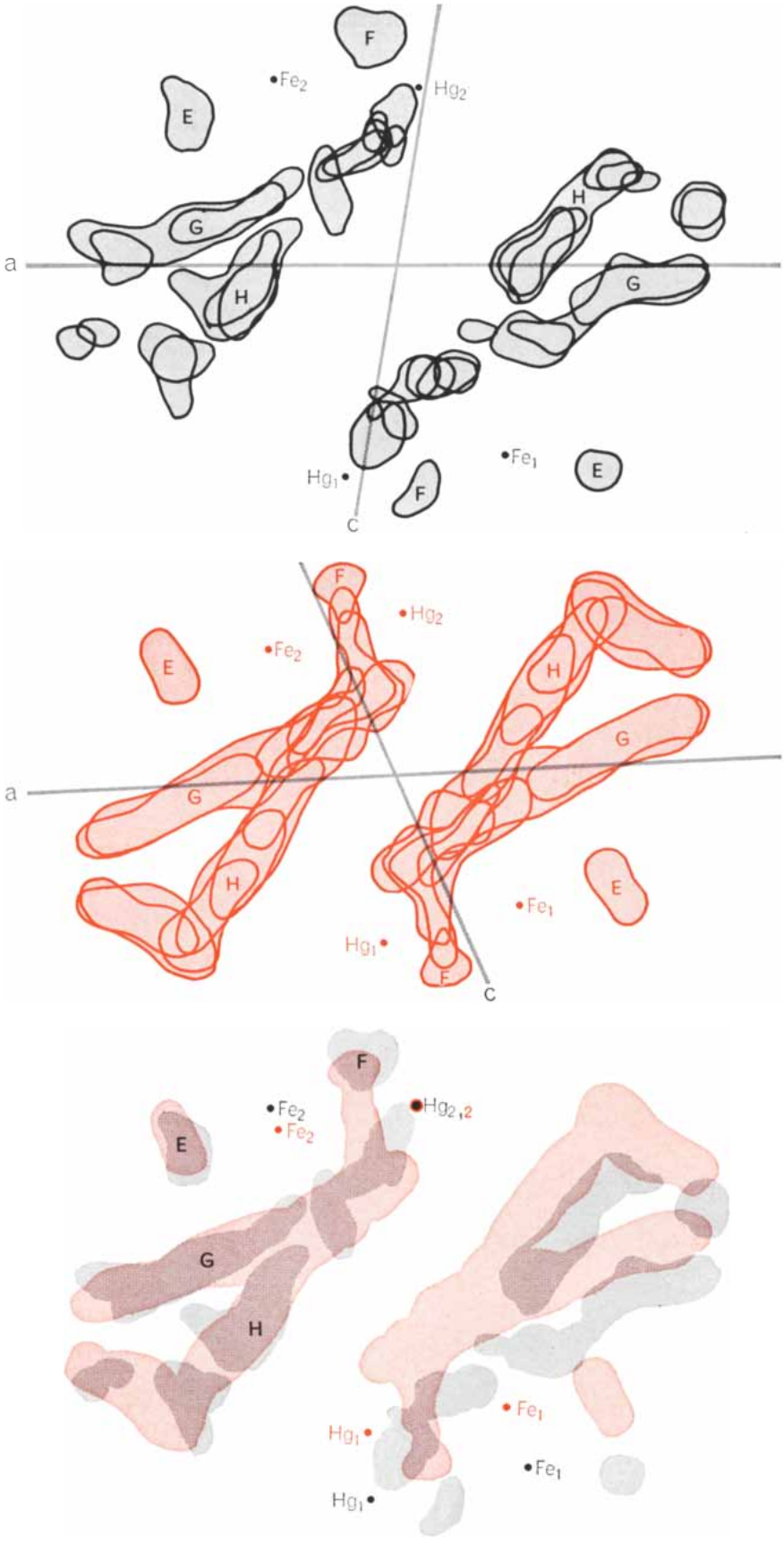
Certain anemia patients suffer from a shortage of alpha chains; the beta chains, robbed of their usual partners, group themselves into independent assemblages of four chains. These are known as hemoglobin *H* and resemble normal hemoglobin in many of their properties. Reinhold Benesch and Ruth E. Benesch of the Columbia University College of Physicians and Surgeons have discovered, however, that the four iron atoms in hemoglobin *H* do not interact, which led them to predict that the combination of hemoglobin *H* with oxygen should not be accompanied by a change of structure. Using crystals grown by Helen M. Ranney of the Albert Einstein College of Medicine, Lelio Mazzarella and I verified this prediction. Oxygenated and reduced hemoglobin *H* both resemble normal human reduced hemoglobin in the arrangement of the four chains.

The rearrangement of the beta chains must be set in motion by a series of atomic displacements starting at or near the iron atoms when they combine with oxygen. Our X-ray analysis has not yet reached the resolution needed to discern these, and it seems that a deeper understanding of this intriguing phenomenon may have to wait until we succeed in working out the structures of reduced hemoglobin and oxyhemoglobin at atomic resolution.

Allosteric Enzymes

There are many analogies between the chemical activities of hemoglobin and those of enzymes catalyzing chemical reactions in living cells. These analogies lead one to expect that some enzymes may undergo changes of structure on coming into contact with the substances whose reactions they catalyze. One can imagine that the active sites of these enzymes are moving mechanisms rather than static surfaces magically endowed with catalytic properties.

Indirect and tentative evidence suggests that changes of structure involv-



MOVEMENT OF HEMOGLOBIN CHAINS was discovered by comparing portions of the two beta chains in "reduced" (oxygen-free) human hemoglobin (*top*) with the same portions of horse hemoglobin containing oxygen (*middle*). The bottom illustration shows the outlines of the top and middle pictures superposed so that the mercury atoms (Hg_2) and helical regions (*E, F, G, H*) of the two chains at left coincide. The iron atoms (Fe_2) do not quite match. The chains at right are now seen to be shifted with respect to each other.

ing a rearrangement of subunits like that of the alpha and beta chains of hemoglobin do indeed occur and that they may form the basis of a control mechanism known as feedback inhibition. This is a piece of jargon that biochemistry has borrowed from electrical engineering, meaning nothing more complicated than that you stop being hungry when you have had enough to eat.

Constituents of living matter such as amino acids are built up from simpler substances in a series of small steps, each step being catalyzed by an enzyme that exists specifically for that purpose. Thus a whole series of different enzymes may be needed to make one amino acid. Such a series of enzymes appears to have built-in devices for ensuring the right balance of supply and demand. For example, in the colon bacillus the amino acid isoleucine is made from the amino acid threonine in several steps. The first enzyme in the series has an affinity for threonine: it catalyzes the removal of an amino group from it. H. Edwin Umbarger of the Long Island Biological Association in Cold Spring Harbor, N.Y., discovered that the action of the enzyme is inhibited by isoleucine, the end product of the last enzyme in the series. Jean-Pierre Changeux of the Pasteur Institute later showed that isoleucine acts not, as one might have expected, by blocking the site on the enzyme molecule that would otherwise combine with threonine but probably by combining with a different site on the molecule.

The two sites on the molecule must therefore interact, and Jacques Monod, Changeux and François Jacob have suggested that this is brought about by a rearrangement of subunits similar to that which accompanies the reaction of hemoglobin with oxygen. The enzyme is thought to exist in two alternative structural states: a reactive one when the supply of isoleucine has run out and an unreactive one when the supply exceeds demand. The discoverers have coined the name "allosteric" for enzymes of this kind.

The molecules of the enzymes suspected of having allosteric properties are all large ones, as one would expect them to be if they are made up of several subunits. This makes their X-ray analysis difficult. It may not be too hard to find out, however, whether or not a change of structure occurs, even if it takes a long time to unravel it in detail. In the meantime hemoglobin will serve as a useful model for the behavior of more complex enzyme systems.

How to keep a Corporation Young

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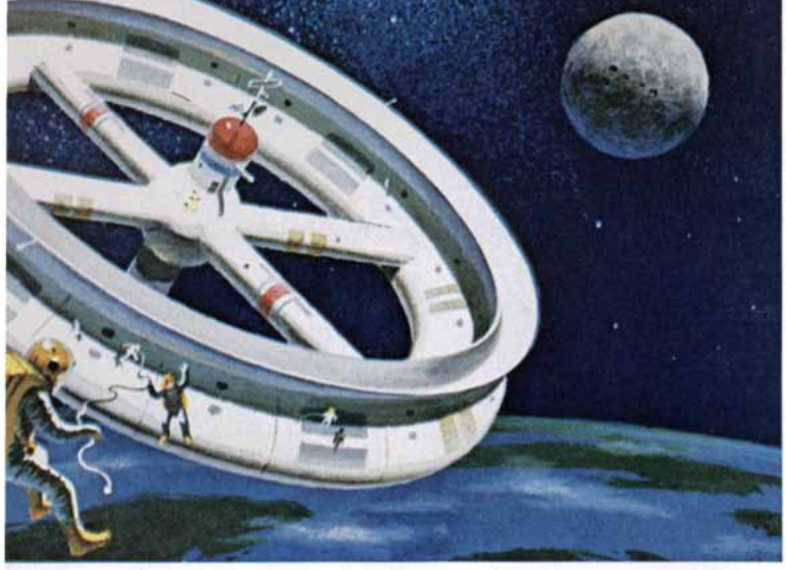
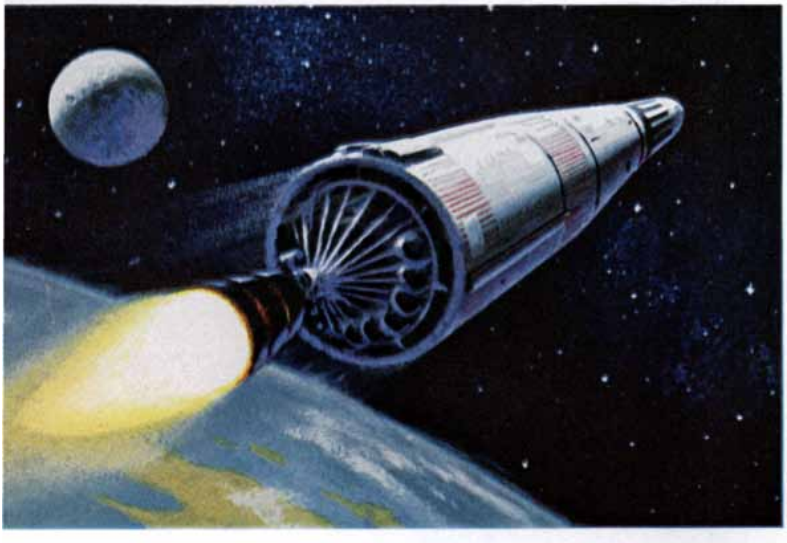
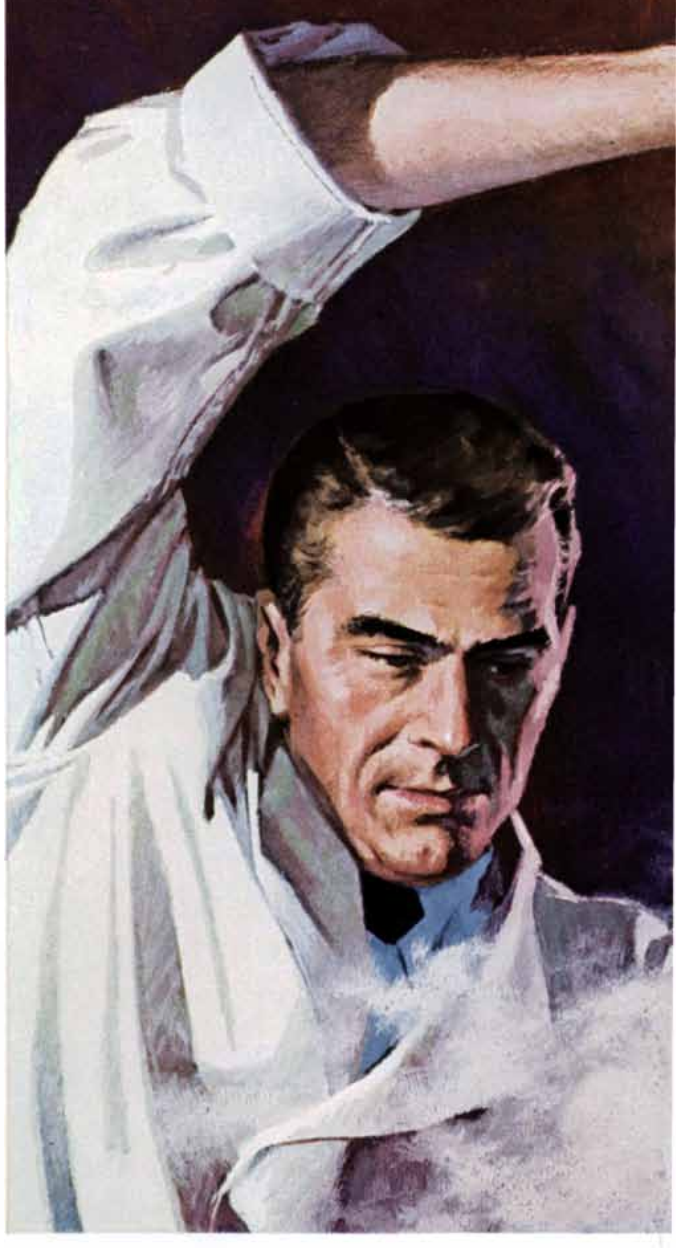


Superconductive magnetic fields will protect space travelers from deadly radiation.



Superconductive magnets will shape the plasmas of jet propulsion engines for space travel.



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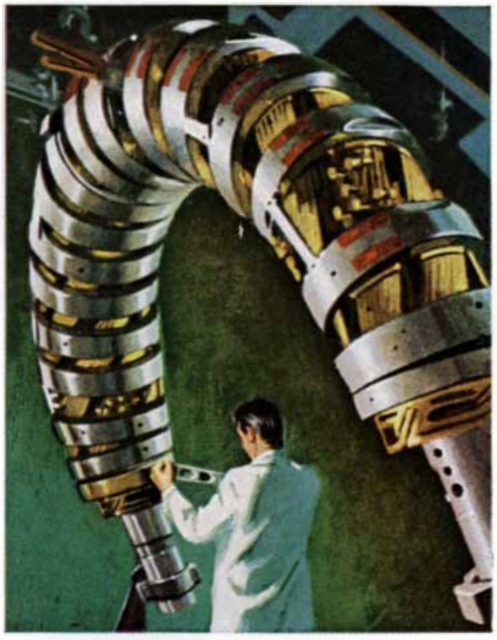

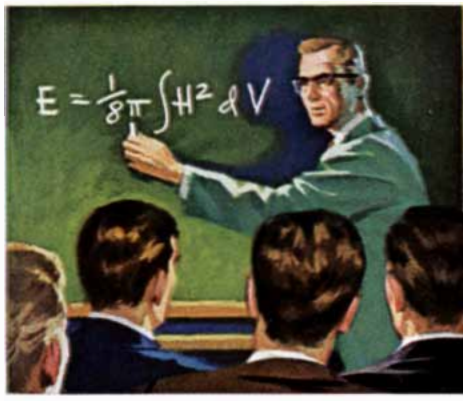

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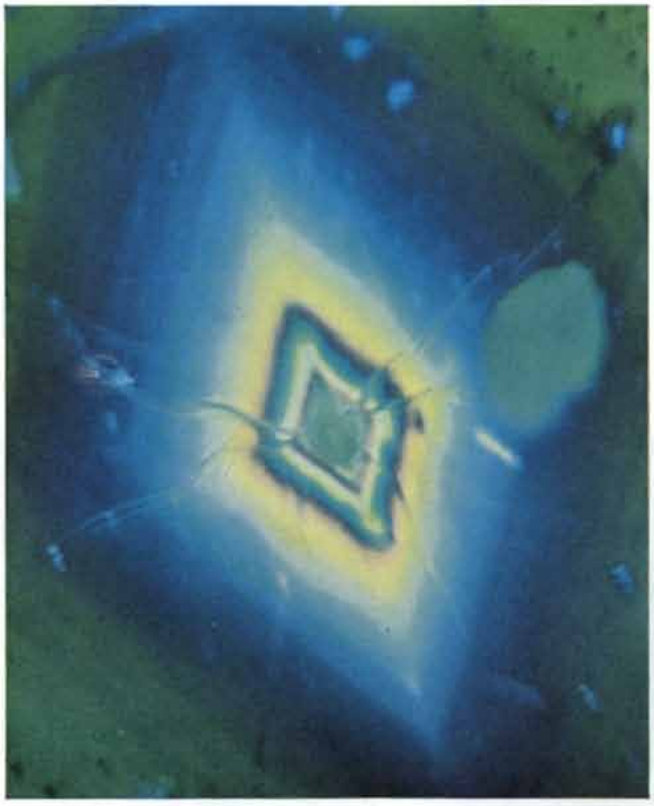


GROWTH SPIRAL in a crystal of polyethylene is revealed by the interference microscope. Such a spiral occurs when the polyethylene molecules in a dilute solution form a thin plate that as it grows regularly turns back on itself like a winding staircase.

DENDRITIC CRYSTALS of polyethylene resemble similar crystals of snow. These crystals formed in a dilute solution of polyethylene that was rapidly cooled. Here they are flattened on the microscope slide; when they float, they curl up into spherical shapes.

SPHERULITES are dendritic crystals that have formed in solid polyethylene as it has cooled from the molten state. Here the sixfold symmetry of the crystals at top right on this page is not visible; the crystals evince themselves by the regular color pattern that appears when the material is viewed in monochromatic light and between two crossed polarizing filters. This photomicrograph was made by Anton Peterlin of the Research Triangle Institute in Durham, N.C. The two at top of page were made by the author.

The Solid State of Polyethylene

The chainlike molecules of polyethylene have the curious ability to disentangle themselves and form crystals. The study of nearly perfect crystals can suggest ways to improve all linear polymers

by Bernhard Wunderlich

Polyethylene is the most extensively used plastic; the products made of it range from building materials and electrical insulation to packaging materials and toys. It can be molded into almost any shape, extruded into fiber or filament and blown or precipitated into film or foil. It is also cheap: it currently costs about 25 cents a pound. When polyethylene was introduced in the early 1940's, a few tons of it were made to serve as insulation for high-frequency radar cables; today the annual U.S. production is more than a million tons, a quantity comparable to the annual output of aluminum.

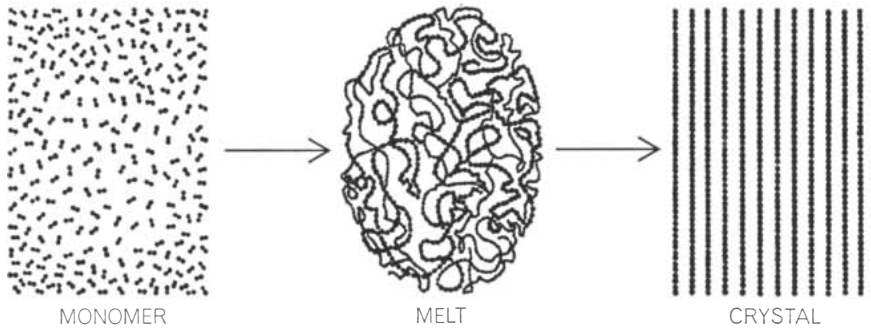
As its name indicates, polyethylene is a polymer of ethylene (C_2H_4); it is the kind of substance in which the molecules of a monomer (in this case ethylene) are assembled into much larger chainlike molecules. All the polyethylene that is manufactured is in the solid state. What is the nature of this solid? Most solids—for example metals—are fundamentally crystalline; that is, their molecules are packed in a regular array. Some solids—for example glass—are amorphous; that is, their molecules have a more random arrangement. Where does polyethylene fit into this picture? If one knew more about its molecular architecture, one could better explain its properties and improve on them. As it turns out, the study of the molecular nature of polyethylene not only has elucidated these properties but also has served as a model for the study of all polymers.

A typical polyethylene molecule is a chain of 10,000 carbon atoms, each of which has two hydrogen atoms attached to it. The distance between the carbon atoms is 1.54 angstrom units and the angle between successive carbon-carbon bonds is 109 degrees; accordingly the molecule can stretch out in a zigzag chain about 12,600 angstroms long and some three angstroms in diameter. If the chain were enlarged 10 million times, it would be 40 feet long and an eighth of an inch in diameter; it would look rather like a 40-foot piece of clothesline.

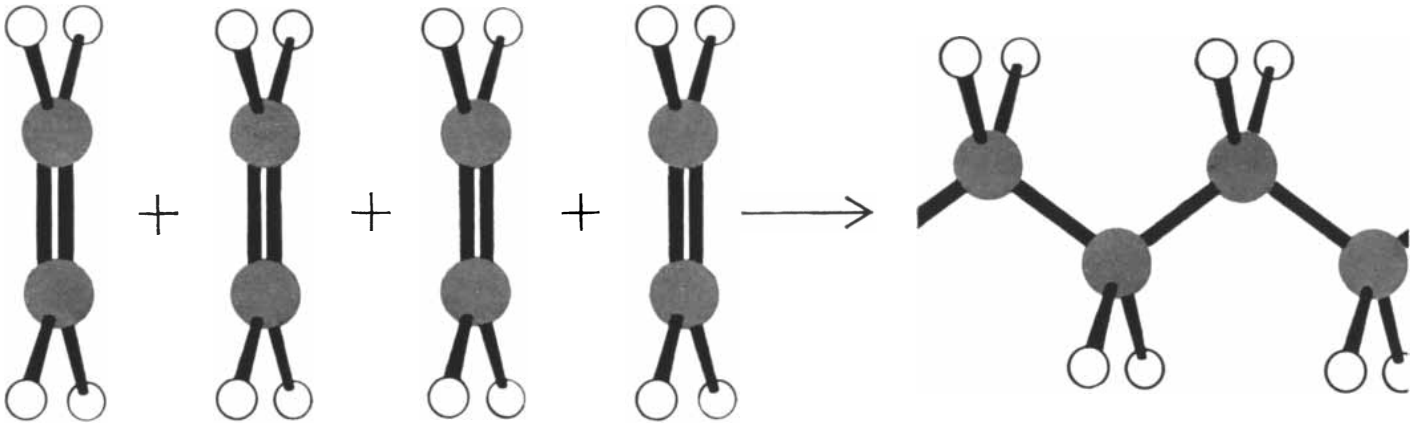
A chain that consists only of simple hydrocarbon (CH_2) links is an ideal version of the polyethylene molecule, which in actuality acquires certain defects during polymerization. At the ends of the chain are groups of atoms whose nature depends on the method of initiation and termination used in synthesizing the molecule. Other defects are due to branching, to the introduction of an occasional unit other than CH_2 into the chain and to later oxidation [*see illustration at bottom of next two pages*]. Although the length of the chain varies, the average polyethylene molecule is so large that these defects scarcely affect its overall composition.

The image of a clothesline is also useful because the polymer molecule is not necessarily stretched out in an orderly manner. Parts of the molecule can be rotated around any carbon-carbon bond from the normal "trans" position to one of two conformations called "gauche" [*see upper illustration on page 84*]. Assuming three alternative conformations for each hydrocarbon unit in the chain, $3^{10,000}$ shapes are possible. Only one of these is all trans, or fully extended. Without any special ordering process the molecule will assume a random coil, and our 40-foot clothesline would be loosely crumpled in a one-foot ball.

No ordering process operates when polyethylene is molten. The random coils are clumped together, with many entanglements within molecules and between them. In a dilute solution polyethylene molecules are also in disarray, but the solvent molecules tend to surround the chain and push its links somewhat apart. If the solution is dilute



STRUCTURE OF POLYETHYLENE is represented in three schematic phases. At left the monomer ethylene is shown as a collection of independent two-carbon molecules. After polymerization long-chain molecules bunch together (*middle*) in a tangled mass. As polyethylene cools from the molten state (described as "the melt"), the long-chain molecules tend to align in regular array, producing a crystal. The bonds between the carbon atoms along the chain are very strong. Weaker cohesive forces bind together the neighboring chains.

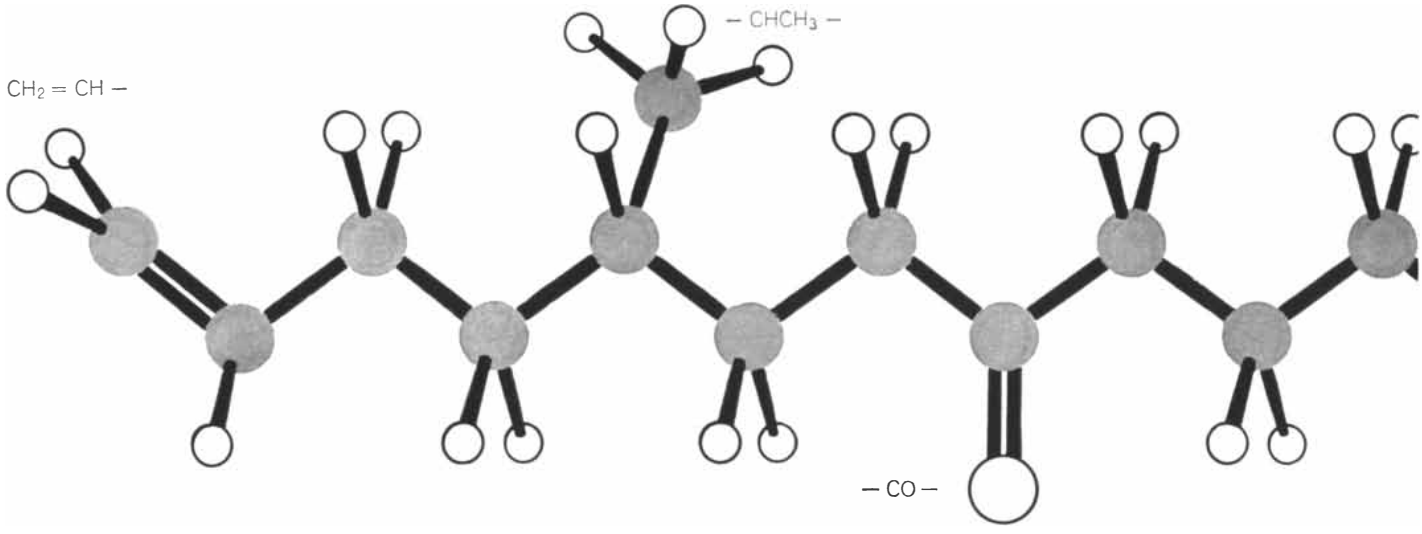


ETHYLENE AND POLYETHYLENE are related as monomer and polymer as indicated here. The ethylene molecule (*four samples are at left*) is a pair of doubly bonded carbon atoms with two hydrogen atoms extending from each. A section of polymer chain is shown at right. Although the chain length of polyethylene molecules varies greatly, an average chain contains 10,000 carbon atoms,

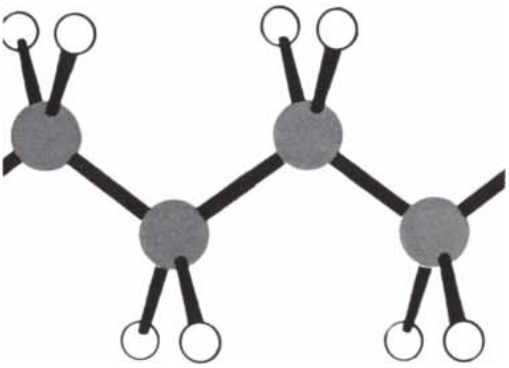
enough, the molecules may be separated from one another and not mutually entangled. In both the melt and in solution segments of the polyethylene chain vibrate and continuously change their conformation. Because rotation around the carbon-carbon bonds requires a certain amount of energy, the rate of change from one conformation to another is determined by temperature [*see lower illustration on page 84*]. When a molten polymer cools, the changes occur more slowly and the viscosity of the melt rises until, at a point called the glass-transition temperature, the conformations are fixed and a solid results. For polyethylene the glass transition begins at about minus 23 degrees centigrade.

Long before the cooling polyethylene reaches the glass transition it goes through an ordering process: it tends to crystallize, segments of its molecules becoming fixed in a regular array. The chains extend into the all-trans conformation, which allows them to be closely packed. The process is accompanied by a significant release of energy: the heat of crystallization. Where adjoining polyethylene chains line up parallel to one another, forming a three-dimensional crystal lattice, ordered regions can be detected by X-ray diffraction and occasionally can be seen by optical microscopy. These crystalline regions are stronger than the noncrystalline ones, and hence strengthen the material.

The crystallization of long-chain polyethylene molecules differs instructively from the crystallization of spherical atoms—for example the atoms of gold. If we imagine a crystal of gold as a regular stack of cannonballs and a crystal of polyethylene as a stack of logs, we can begin to see that the two types of crystal have different properties when they are tested in different directions. In the polyethylene crystal there is very strong bonding along the chain and only weak bonding between chains. The carbon-carbon bonds of the chain are as strong as the bonds in diamond, but the hydrocarbon-hydrocarbon bonds between chains are as weak as those in paraffin. This anisotropy—the difference in properties with direction—is the basis for the high strength of polyethylene in the direction of its polymer chains and its relative weakness at right angles to this direction. Gold, on the other hand, is composed of atoms that are bonded with equal strength to all 12



DEFECTS in the polyethylene molecule are exemplified by six irregularities. The end group at left is a doubly bonded pair of carbon atoms from which three hydrogens extend. Farther to the right along the chain there is a carbon attached to a methyl



each 1.54 angstrom units from its neighbor. Such a chain is proportional to a rope 40 feet long and an eighth of an inch across.

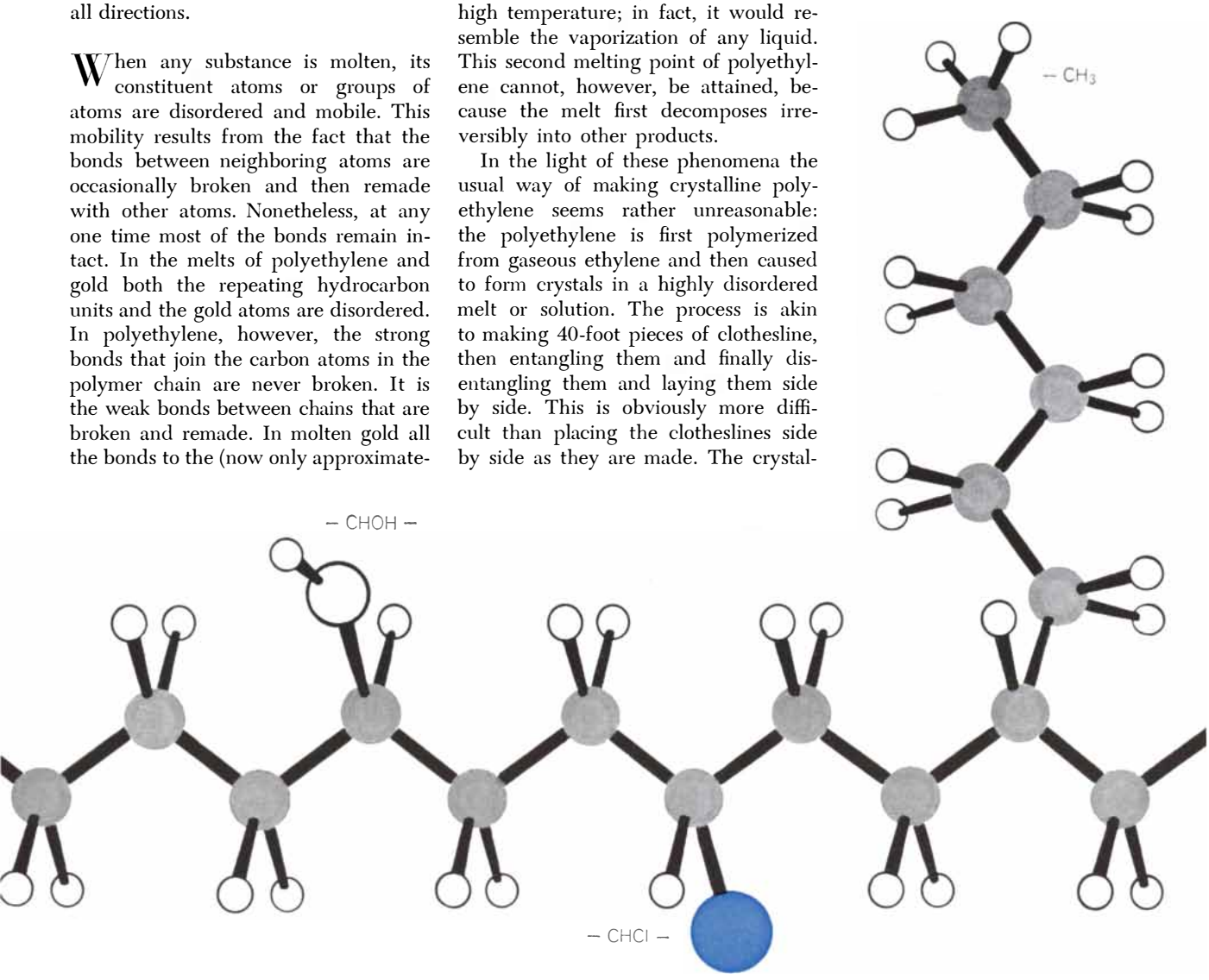
of their neighboring atoms, and it therefore has virtually the same strength in all directions.

When any substance is molten, its constituent atoms or groups of atoms are disordered and mobile. This mobility results from the fact that the bonds between neighboring atoms are occasionally broken and then remade with other atoms. Nonetheless, at any one time most of the bonds remain intact. In the melts of polyethylene and gold both the repeating hydrocarbon units and the gold atoms are disordered. In polyethylene, however, the strong bonds that join the carbon atoms in the polymer chain are never broken. It is the weak bonds between chains that are broken and remade. In molten gold all the bonds to the (now only approximately) 12 neighboring atoms can be broken and remade. Molten gold is no more disordered with respect to its crystalline state than molten polyethylene is, because of the many conformations the polymer chain can take by rotation around carbon-carbon bonds. The difference in melting point (1,063 degrees C. for gold and 142 degrees for polyethylene) is due entirely to the difference in the energy of the bonds in the respective melts and solids.

Since the sequence of hydrocarbon units along the chains of polyethylene in a melt remains perfect, we can look for a second "melting" point at which this sequence is destroyed by depolymerization, or decomposition. If polyethylene could be depolymerized into ethylene, which at ordinary temperatures is a gas, the increase in disorder during depolymerization would be comparable to the evaporation of gold at high temperature; in fact, it would resemble the vaporization of any liquid. This second melting point of polyethylene cannot, however, be attained, because the melt first decomposes irreversibly into other products.

In the light of these phenomena the usual way of making crystalline polyethylene seems rather unreasonable: the polyethylene is first polymerized from gaseous ethylene and then caused to form crystals in a highly disordered melt or solution. The process is akin to making 40-foot pieces of clothesline, then entangling them and finally disentangling them and laying them side by side. This is obviously more difficult than placing the clothelines side by side as they are made. The crystallization of gold, in contrast, is akin to stacking marbles one by one in a box. No one has succeeded, however, in making a crystalline polymer by means of simultaneous polymerization and crystallization.

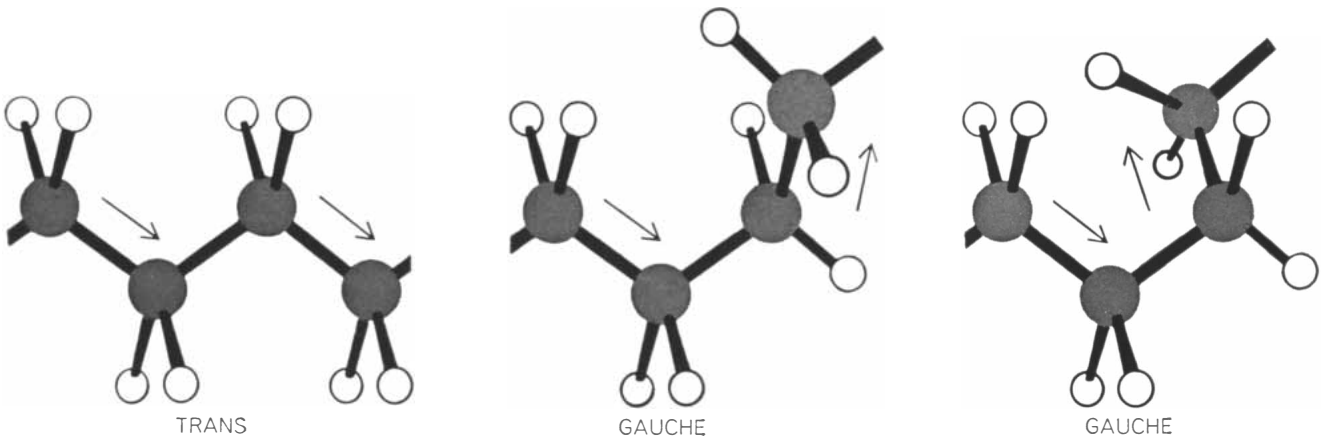
The first successful investigations of crystalline polyethylene were conducted in 1939 by C. W. Bunn in Britain. Bunn made his crystalline material by stretching extruded fibers of polyethylene. The stretching encouraged the polymer chains to lie parallel; the result was a material that was sufficiently crystalline to indicate the nature of perfect crystals of polyethylene. It was clear that the crystals in the material were not perfect because they were smaller than the length of the



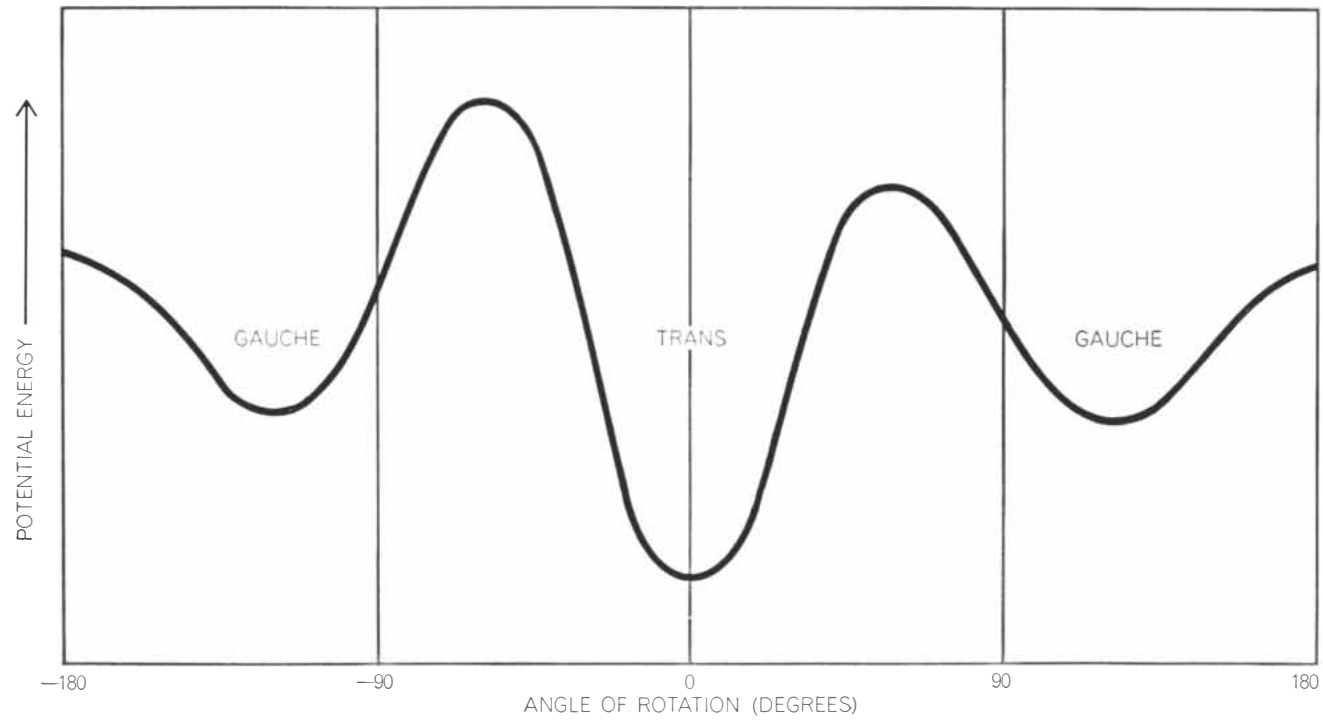
group (CH_3). There follows a carbon doubly bonded to an oxygen atom, a carbon bonded to a hydroxyl group (OH) and a carbon bonded to a chlorine atom. At top right a branch extends from the molecule. Such defects can markedly alter crystalline properties.

polymer chains. The picture that developed from this experiment and experiments with other polymers was that segments of the polymer chain formed crystals and that the remaining segments of the chain meandered without order into other crystalline regions.

The next advance came when another means of crystallization was used, namely crystallization from dilute solution. Since the polymer molecules in a dilute solution are separated from one another, a crystal can be built up by the addition of one molecule at a time. The big surprise was that polyethylene molecules did so quite easily. They crystallized in the manner that someone faced with the task of putting a large number of clotheslines in order would adopt: winding them up and then stacking the wound packets. Andrew Keller in Britain, Erhard W. Fischer in Germany and P. H. Till, Jr., in the U.S. each discovered in 1957 that polyethylene crystallizes from dilute solution in the form of single crystals made up of folded polymer chains. Electron micrographs showed that thin lamellae—plates about 100 angstroms thick and 10,000 angstroms across—formed on slow cooling of the solution. Given such dimensions, a gram of crystal would contain 100,000 billion lamellae with a total



THREE STABLE POSITIONS that carbon atoms assume when bonded together in a chain are compared. If all the carbon atoms of the chain were in the "trans" position shown at left, the molecule would assume its most extended shape. In each "gauche" position (*middle and right*) the carbon atom at right has undergone a 120-degree rotation that changes the shape of the molecule. Since any one of the three conformations can exist around any one of its 10,000 carbon-to-carbon bonds, the polyethylene molecule can assume a huge number of shapes. The energy needed to effect the shift from the trans to gauche position can be provided by heat.



POTENTIAL ENERGY required to rotate one of two neighboring carbon atoms past the other and into a new position is charted. The low point in the middle of the curve represents the energetically favored trans conformation; the low points at left and right represent the gauche positions. The difference between the low points is some 800 calories per mole. To force a carbon atom and its associated groups over the highest peak takes about 4,000 calories per mole. One mole is the weight in grams of 6×10^{23} atoms.

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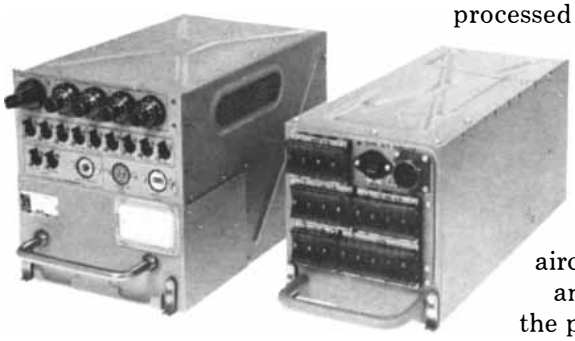

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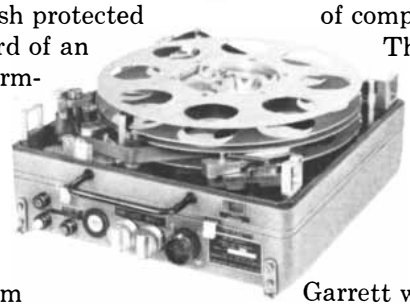

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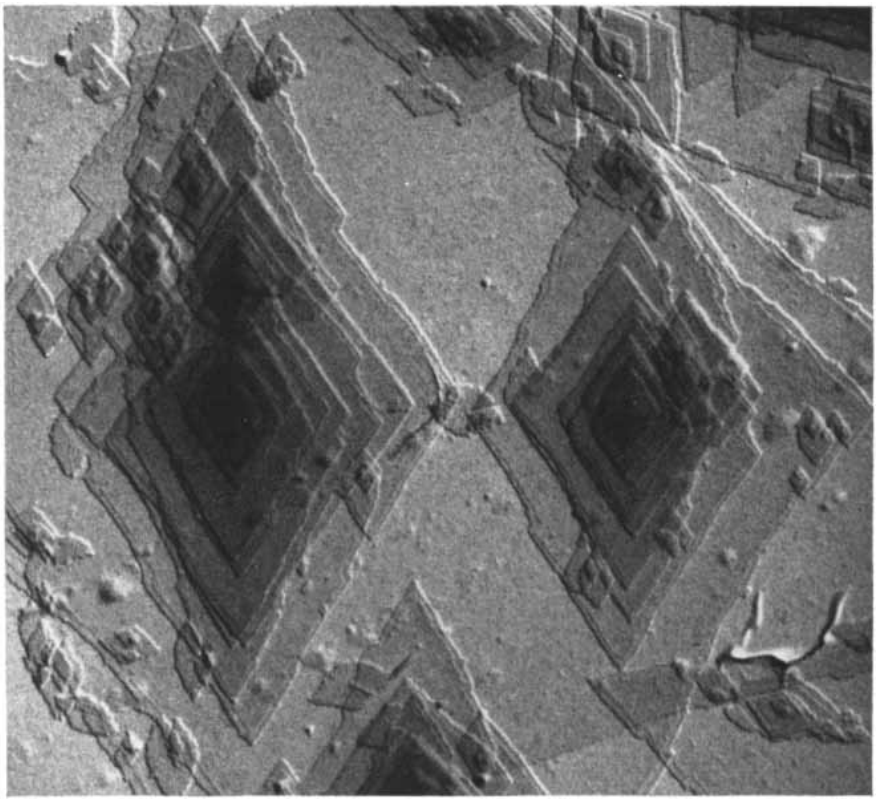
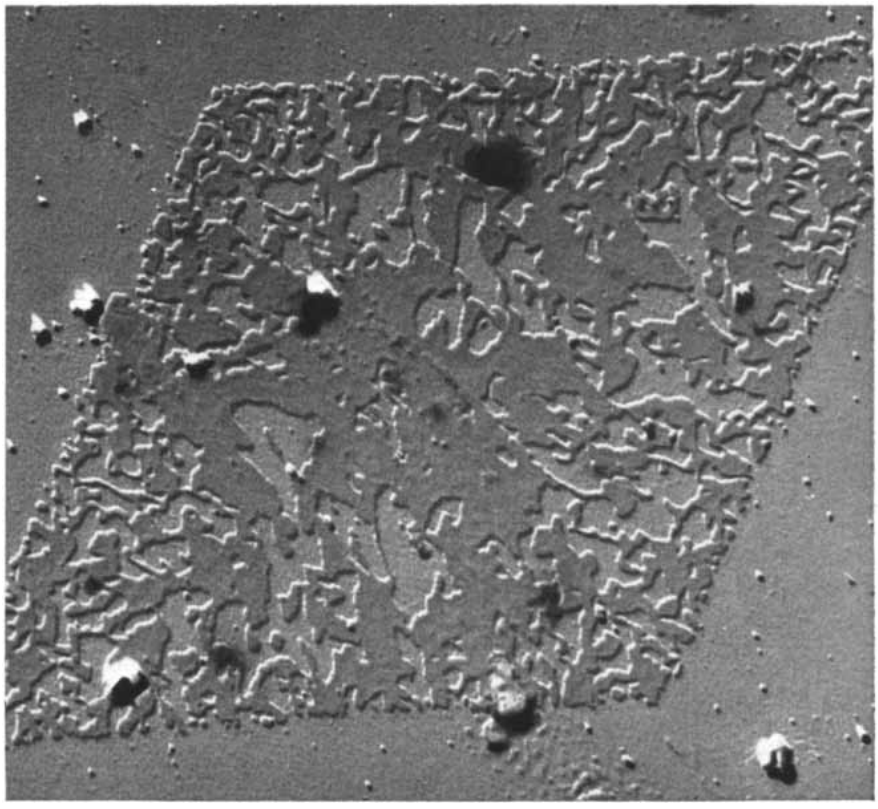


LAMELLAE of a polyethylene crystal are magnified 20,000 times in this electron micrograph made by Andrew Keller of the University of Bristol. Since the molecular chains are oriented at right angles to the micrograph they must fold sharply at top and bottom.



THICKENED CRYSTAL can be formed as heat increases the length of the chain between the folds in the molecules that make up the lamellae. The thickness of the lamella shown here was thus increased from 100 angstrom units to 200. As the photograph reveals, however, holes must form in the process, since a thicker crystal requires more material.

surface area of about a million square centimeters. Although the crystals are exceedingly small, one can establish by electron diffraction that the chains are oriented at right angles to the flat surface of the lamella. This means that they must bend sharply every 100 angstroms or so and that a chain of 10,000 carbon atoms would form perhaps 126 folds. The whole crystal would contain about 40,000 chain molecules.

With the discovery of these tiny but apparently perfect crystals the study of polymers in the solid state had come of age. Once the properties of the crystals were understood one could hope to understand less perfect aggregates. In 1958, while working at Cornell University, I began trying to make bigger crystals of polyethylene in the hope that the material could be studied more conveniently by means of optical microscopy. The first problem to be solved arose from the fact that lamellae of polyethylene are transparent and therefore invisible in the conventional microscope. This difficulty was surmounted by the use of interference microscopy, a technique in which a crystal is made visible by the fact that the light used for observation is separated into two beams. One beam is directed through the crystal and the other passes next to it; the beams are accordingly retarded by different amounts. When the two beams are recombined, their waves interfere; the interference extinguishes some of the colors in white light, giving rise to other colors that outline the crystal structures. If monochromatic light is used instead of white light, the intensity of interference can be accurately determined and the thickness of a large crystal can be measured to within six angstroms.

As for making the crystals bigger, one method is to introduce a growth spiral, in which a single lamella grows in such a way as to regularly turn back on itself like a winding staircase [*see illustration at top left on page 80*]. In this way the lamella can form a structure some 150 layers thick. The layers are still quite thin and flexible; if they are not somehow flattened, as by depositing them on a flat surface for microscopy, they bend upward or downward and form a structure that is almost spherical.

This raises the question of why it is that only thin, folded-chain lamellae grow from a dilute solution of polyethylene. A tentative description of how

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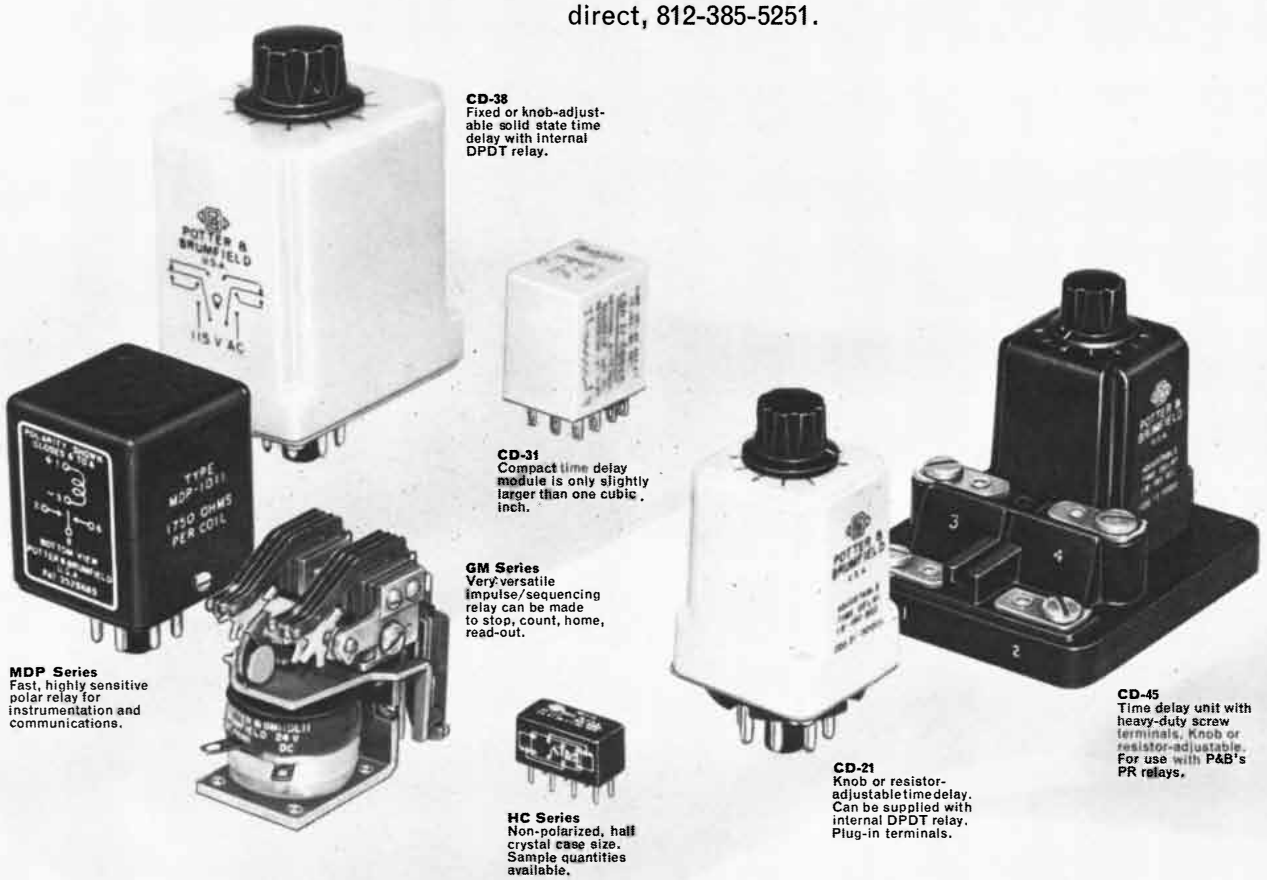

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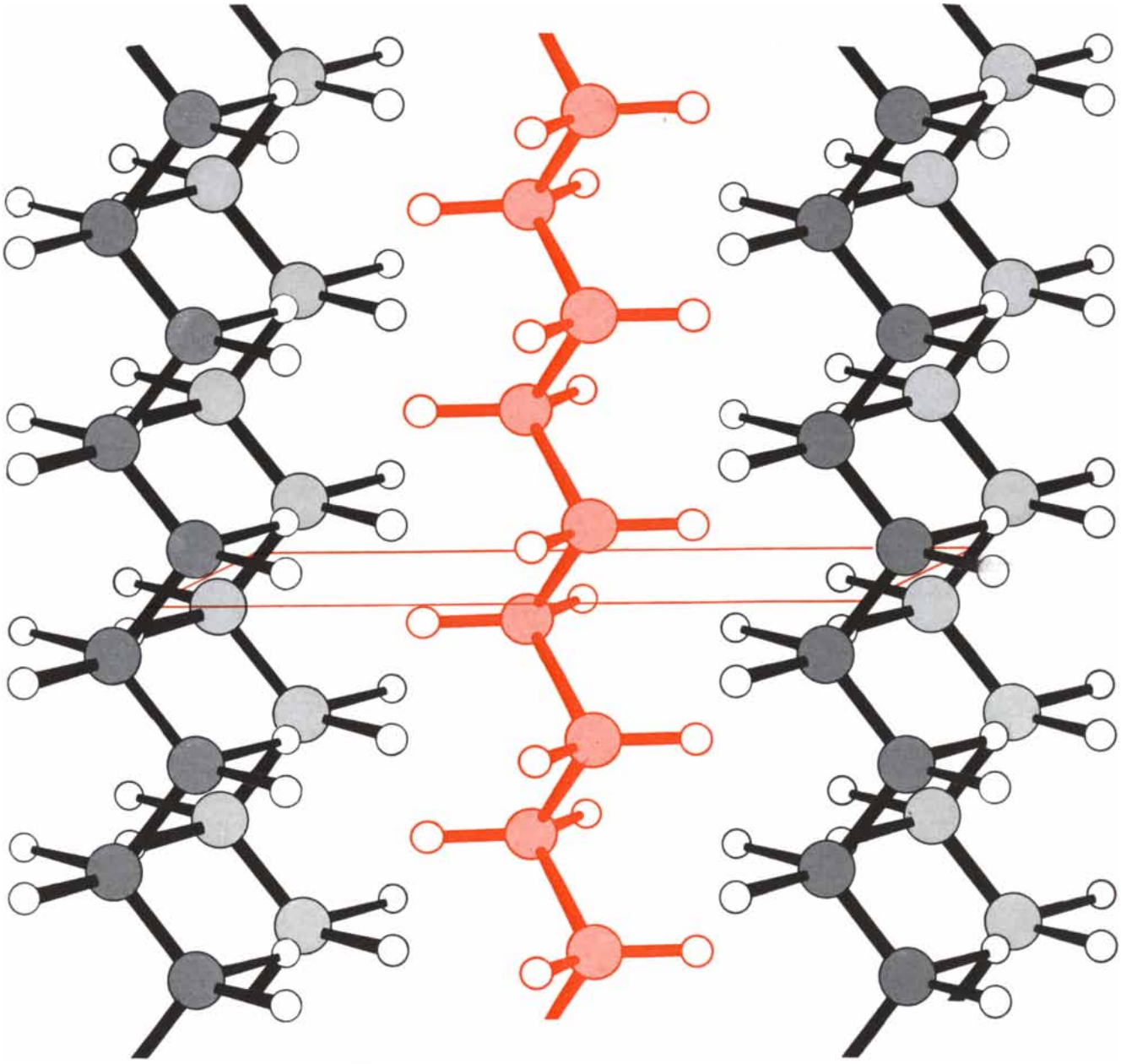
the lamellae develop can now be given. When long-chain molecules form a crystal, they do so faster if they proceed by segments of chain, that is, by folding after fixed lengths have crystallized. On the other hand, in a crystal an extended chain would be more stable than a folded one, which means that folded chains in a crystal try to straighten out. If the process of folding is taking place at a comparatively low temperature, as it does in crystallization from a dilute solution, not much comes of the straightening process before more layers of folded chain form on top of the ones laid down earlier. The resulting crystal is therefore only partly stable.

On the basis of this picture one can undertake to increase the thickness of polyethylene crystals. The first step would be to increase the mobility of the polymer chains so that, as they form crystals, they can straighten out to a greater degree. If the temperature of crystallization is higher, the chains do tend to fold in longer segments; the resulting crystal is therefore thicker. Even crystals that have already formed become thicker when the temperature is raised sufficiently above the original temperature of crystallization. As the chains in such crystals extend, however, they require less room at right angles to the surface of the crystal and space is left between them. Thus the thickened crystal is full of holes.

Numerous experiments in this country and abroad indicate that the thickening of polyethylene crystals by this process proceeds at a rate that is predictably related to temperature. The formation of crystals by the addition of folded chains proceeds at another rate that is also related to temperature. Under ordinary conditions of crys-



MOLECULAR CHAINS of polyethylene in the crystalline state fall into a precisely ordered pattern. Four chains similarly oriented pass through the corners of a rectangular lattice; a fifth chain, rotated with respect to the other four, passes through the center.

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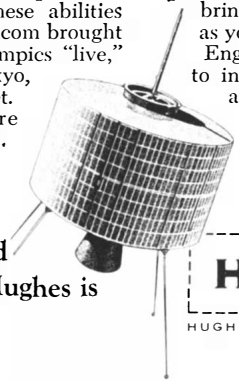

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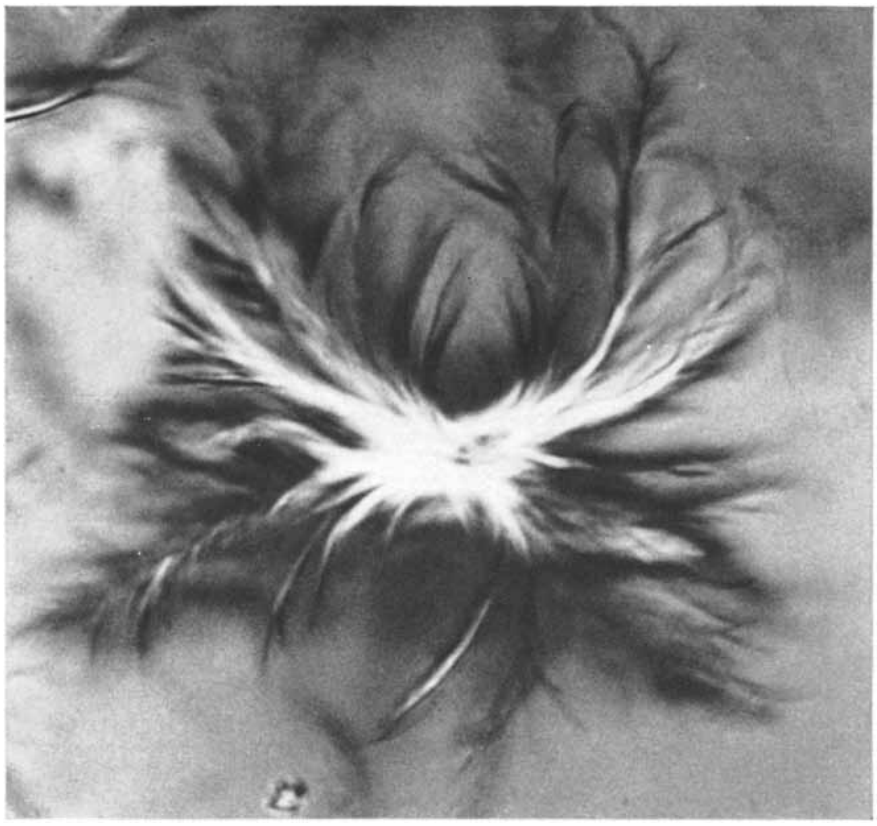
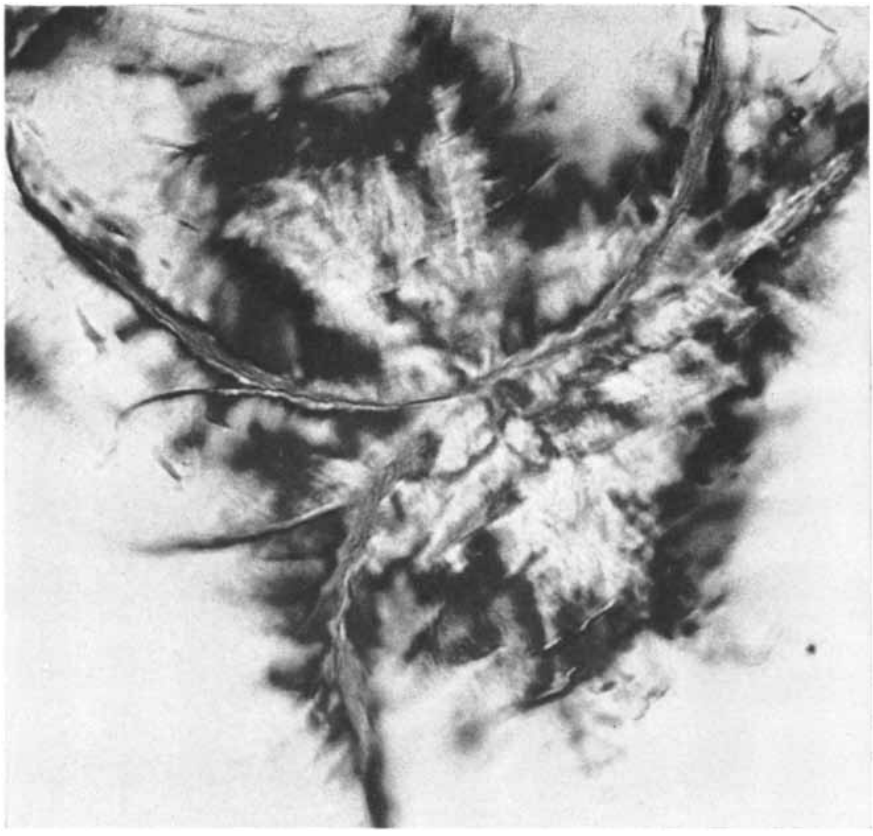


ALMOST SPHERICAL DENDRITE of polyethylene crystallized from solution is shown floating on its side. Central "X" shape results from the turning up of primary branches.



ALMOST FLATTENED DENDRITE seen from above has one branch turned up on both ends, indicating its flexibility. Both micrographs on this page were made by the author.

tal growth the latter rate is much faster. This means that only folded-chain crystals form, and, as we have seen, such crystals can only be made to thicken into imperfect crystals by subsequent heat treatment.

According to this view one should be able to grow thicker crystals by altering the two rates to favor the process of extended-chain crystallization. A stratagem that immediately comes to mind is to raise the pressure of the environment in which the crystals form. With every 1,000 atmospheres of added pressure the temperature at which polyethylene crystallizes rises by 20 degrees C.; this increase in temperature offsets the slowing down of crystallization that results from the increase in pressure. What is now important is that, as has been mentioned above, polymer crystals are anisotropic: they are more compressible in a direction at right angles to their molecular chains than they are in a direction parallel to the chains. Pressure from all directions thus has a greater effect on processes that act at right angles to the chains. The result is to slow down the crystal growth at right angles to the chains and favor their straightening.

By raising the pressure of molten polyethylene to 5,000 atmospheres it was possible to grow crystals from the melt that were 30,000 angstroms thick—300 times thicker than the lamellae grown in solution at ordinary pressures, and as thick as the molecules are long. When such crystals are fractured and viewed in the electron microscope, one can see many parallel striations that run all the way through the crystal. These striations are evidence of the straightness of the polymer chains; they resemble the striations in fractured asbestos, which are also due to the fibrous nature of the material. It is not inconceivable that someday one could grow perfect crystals of polyethylene an inch across in the direction of the chains.

There is much of interest, however, in polyethylene crystals grown under less favorable conditions. Lamellae of polyethylene grow from dilute solution only in a temperature range of five degrees C.; thicker crystals grow from a melt under pressure only in a temperature range that is similarly narrow. What kinds of crystal grow under other conditions? If a dilute solution of polyethylene is rapidly cooled, the crystals that form in it have the shape of dendrites: feathery four-sided or six-sided

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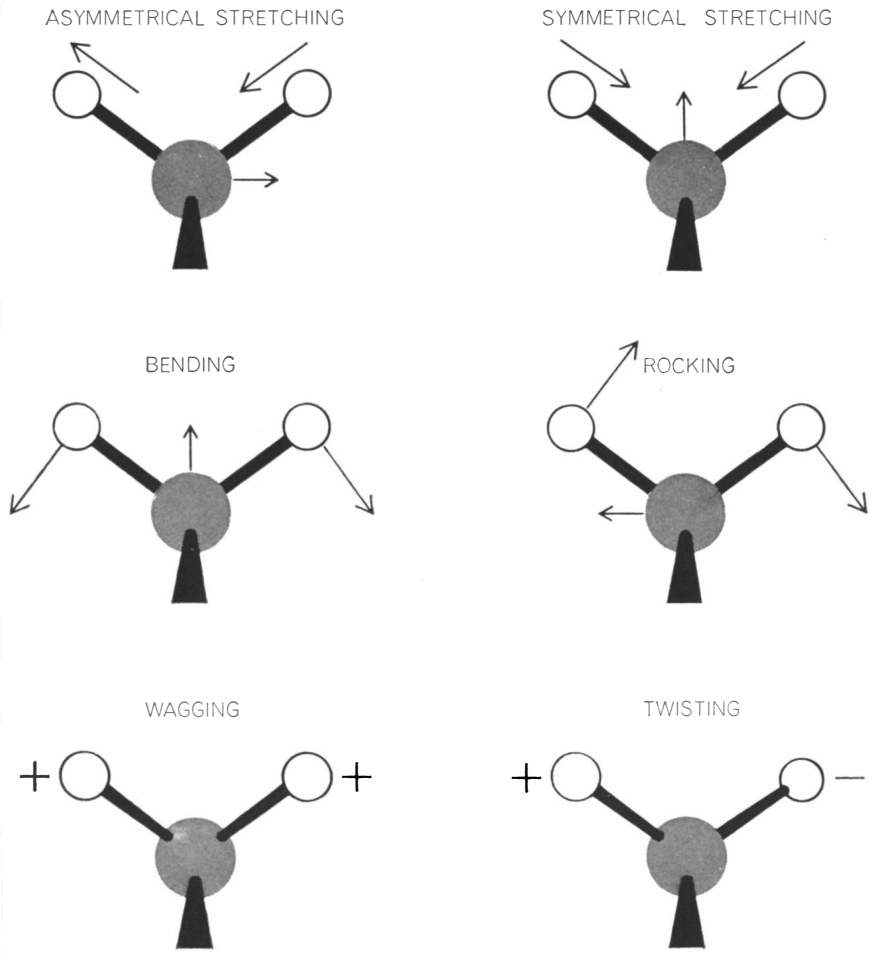
structures that resemble similar crystals of snow. The dendritic pattern is most clearly visible when the crystals are deposited on a flat surface [*see illustration at top right on page 80*]. Since the separate branches of the dendrite are only 100 angstroms thick, they are quite flexible; when they are afloat, they bend upward or downward into a spherical configuration.

Dendritic shapes also grow from a melt; indeed, most of the crystalline regions in ordinary polyethylene are dendritic. Dendrites that form under such conditions have much more feathery arms than those that grow in solution, and they cannot be resolved by the light microscope. They can, however, be detected by the regular pattern they reveal when they are viewed between two crossed polarizing filters in monochromatic light [*see bottom illustration on page 80*]. In polyethylene crystallized from a melt these regular dendritic regions are called spherulites.

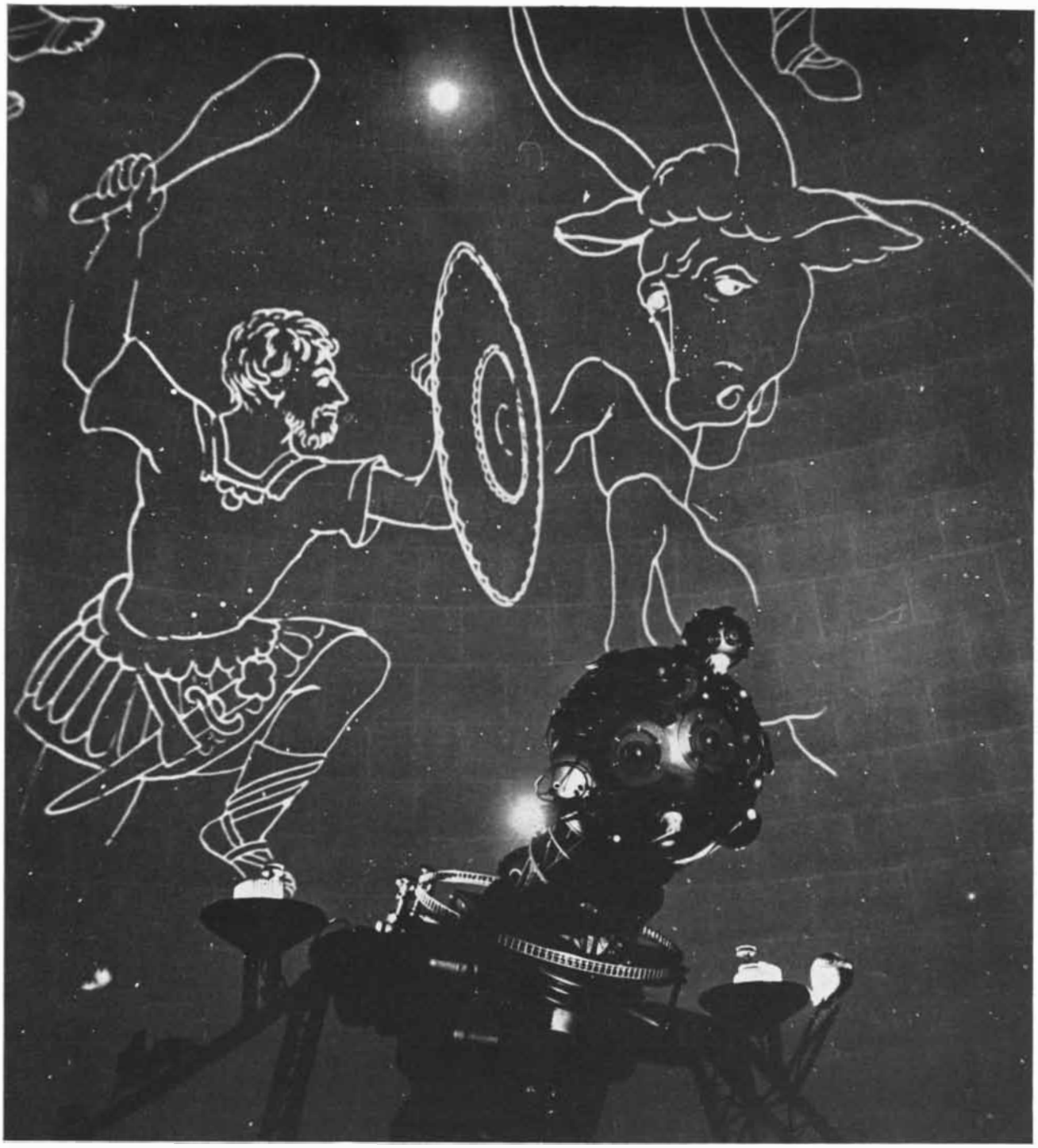
From all the foregoing it will be apparent that the properties of polyethylene must to a large extent be determined by the defects in its crystal structure. How much the defects influence the properties depends on what property one is interested in. We can divide all the properties of polyethylene into two categories: structure-insensitive and structure-sensitive.

Structure-insensitive properties are the volume of a sample of polymer, its compressibility, its heat content and its specific heat (the quantity of heat needed to raise the temperature of the material by one degree C.). Such properties are little influenced by defects. For instance, the volume occupied by CH_2 groups in noncrystalline polyethylene is only about 20 percent greater than that occupied by the same groups in the crystalline material. Where structure-insensitive properties are concerned, it is sufficient to characterize polyethylene rather generally by its "degree of crystallinity." In fact, this degree can be calculated by measuring the volume of a sample of polyethylene with respect to the predicted volume



TYPES OF VIBRATIONS undergone by a carbon atom and its associated hydrogen atoms fixed to a rigid backbone are characterized in this illustration. Because the vibrations lend energy to a polymer, their frequency of occurrence can be calculated from specific-heat data.

Planetaria made in JENA



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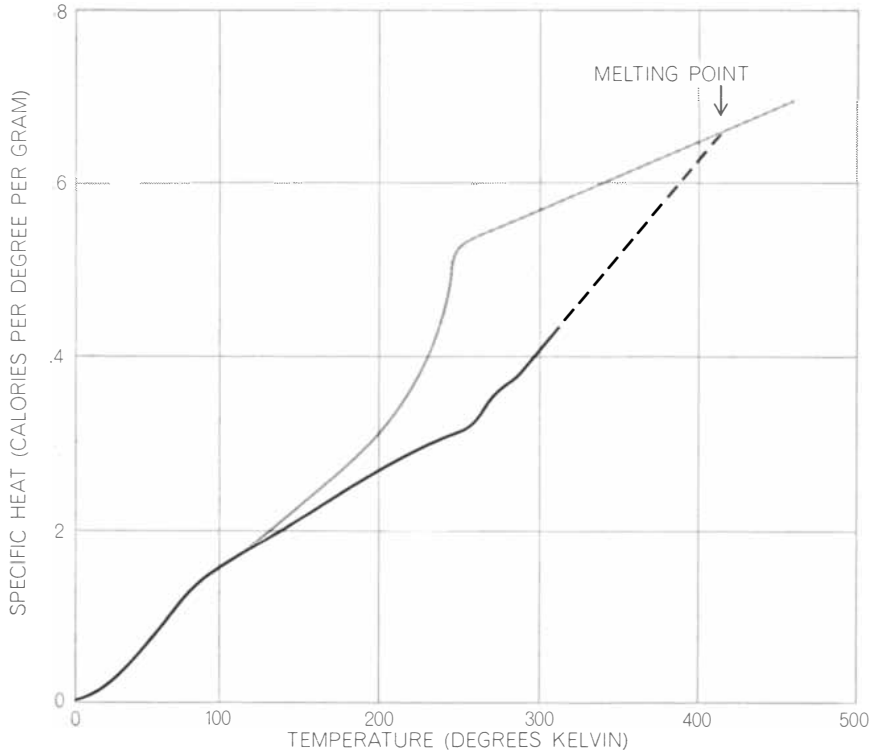
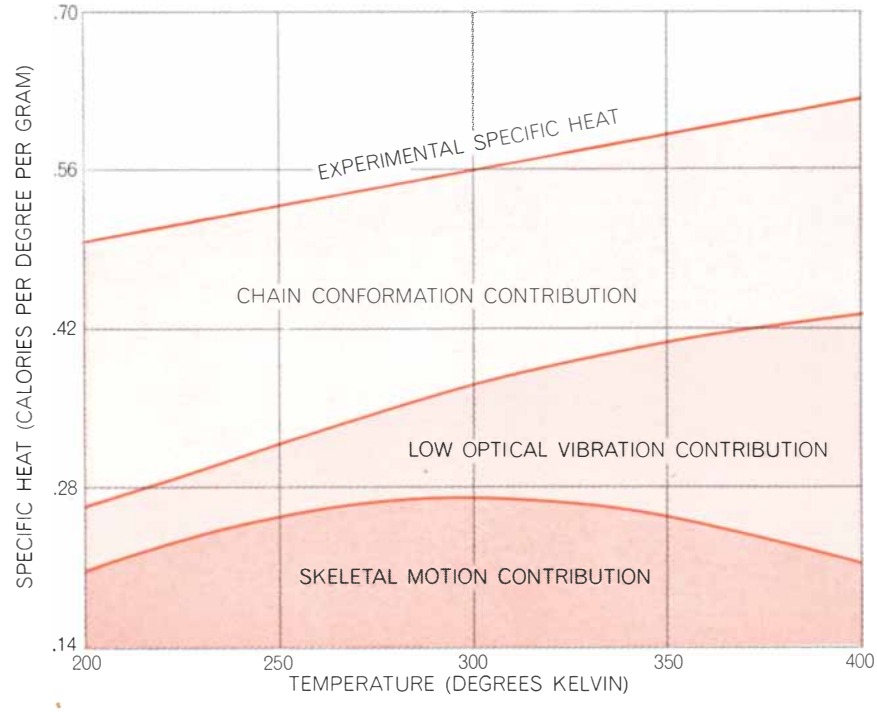


SPECIFIC HEAT, the energy required to raise the temperature of one gram of sample one degree, depends on the crystallinity of the polyethylene. Curves for completely amorphous polyethylene (*upper*) and crystalline polyethylene (*lower*) were extrapolated from the measurable specific heats of polyethylene in varying states of intermediate crystallinity.



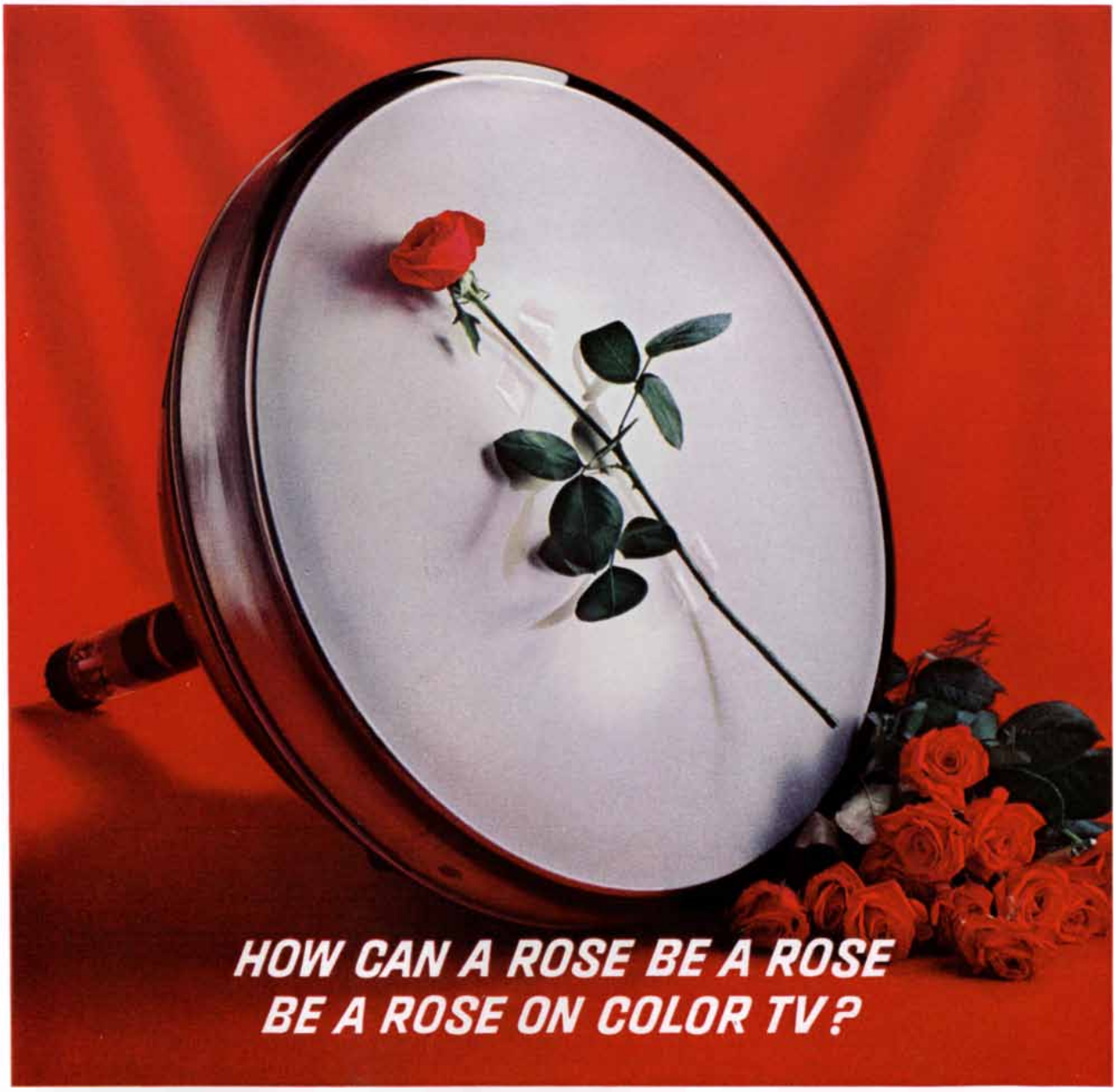
TOTAL ENERGY of a polyethylene sample is indicated by the area under the curve that represents its experimental specific heat (*top*), which is a measure of the calories required to raise the temperature of a gram of polyethylene one degree at a given temperature. Certain types of molecular motion lend energy to this effort. The contribution made by skeletal vibration is charted below the bottom curve. The contribution made by the vibrations characterized as "stretching," "bending," "rocking," "wagging" and "twisting" is charted between the bottom and middle curves. The amount of energy contributed by changes in chain backbone, including those from trans to gauche positions along the chain, is charted below the top curve. Kelvin degrees are degrees centigrade above absolute zero.

of a perfect crystal weighing the same amount.

This is not to say that the study of structure-insensitive properties is not useful to a deeper understanding of the nature of polyethylene and other polymers. For example, the specific heat of a sample of polyethylene can be related to its degree of crystallinity, and this relation can be plotted as a curve [*see top illustration at left*]. Such information can be used to determine the motions of the CH_2 groups in a perfect polyethylene crystal: the different kinds of molecular vibration and their various frequencies [*see bottom illustration at left*]. It can also be used to determine what portions of the specific heat are represented by the molecular motions in an amorphous material. The bump in the specific-heat curve of the amorphous material reflects a diminution in molecular motion starting at about 250 degrees Kelvin (minus 23 degrees C.) that is associated with the transition to the glassy state.

As for the structure-sensitive properties of polyethylene, much less is known about them. Examples of such properties are the maximum strength of the polymer and the rate at which small molecules can diffuse through it. Here a small percentage of crystal defects can change the properties by many orders of magnitude.

Although we have little information about the structure-sensitive properties, we can now begin to see what must be done to obtain it. The key to the problem is knowing enough about the molecular structure of polyethylene to be able to reproduce all the properties of a given sample of the material. This ability has been elusive. Consider, however, what has been done to achieve reproducible melting points in polyethylene. It has been shown that the perfect extended-chain crystal of the material melts at 140 degrees C. and that the folded-chain lamellae of the same material melt at 120 degrees (if one avoids the thickening of the lamellae by heating them faster than the thickening can occur). And the same material with many crystal defects is capable of melting at room temperature. An investigator who had no knowledge of the structural basis of these differences would turn away from this unpredictable substance in disgust. The structural foundation has now been securely laid. We can look forward to a deeper understanding of the nature of polyethylene and other polymers, and to their improvement as materials for man's needs.



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Lateritic Soils

Rich in minerals and poor in organic matter, these soils are common in the Tropics. They present an obstacle to increasing the production of food in many of the underdeveloped nations

by Mary McNeil

In the year 1860 a French naturalist named Henri Mouhot, struggling through the jungles of Indochina in search of plant species, came on a clearing in the tangled wilderness about 150 miles north of Pnompenh, the present capital of Cambodia. Looking up at the sky, he was astonished to see, standing out above the treetops, the sculptured towers of an ancient temple. It proved to be one of the remains of a "lost" civilization that had ruled the area from the ninth to the 16th century. Near the temple was a great walled city, Angkor Thom, with other superb edifices. The wooden parts of these structures had long since rotted away, but the walls, floors, stairs, towers and works of sculpture still stood virtually untouched by time. They were built of sandstone and the extraordinarily durable material known as laterite.

Laterite is a mineral-rich earth that, when exposed to air, turns into a brick-like form of rock (its name comes from the Latin word for brick). It has been an important building material since prehistoric times. Ancient roads were constructed of laterite, and it is still used for highways in parts of southeast Asia and Africa. In modern Thailand many public buildings are built at least in part of laterite. And many communities in India and Africa still rely on laterite, as early man did, as a source of iron.

CHARACTERISTIC COLOR of lateritic soils appears in the aerial photograph on the opposite page. The photograph was taken along the Niger River in Nigeria. In lateritic soil most of the organic material has been leached out, leaving a high concentration of minerals, particularly oxides of iron and aluminum. The iron and aluminum account for the color of lateritic soils, which are usually yellow or a rusty red.

Paradoxically this interesting and useful material may have been one of the principal reasons for the disappearance of the Khmer civilization that built the city of Angkor Thom. Laterites and lateritic soils are disastrous handicaps to agriculture. Today they are known to be major obstacles to the development of many of the underdeveloped countries. Because of laterite, attempts to grow more food in the Tropics may turn much of that region of the earth into wasteland. Laterite is a grave danger to projects such as the flood-control program for the Mekong Valley of southeast Asia [see "The Mekong River Plan," by Gilbert F. White; SCIENTIFIC AMERICAN, April, 1963]. Unless the laterite problem is dealt with, flood control might actually reduce, instead of improve, the food productivity of such areas.

Let us look more closely at this material. It has been a subject of much controversy among geologists and soil scientists. The two groups define laterite somewhat differently. The geologist thinks of laterites primarily as rock or earth aggregates with a high content of iron, aluminum, nickel or manganese. The soil scientist is concerned with the minerals as components of the soil, particularly with the way their role in the soil is affected by weathering and leaching. This article will discuss mainly the "laterization" of soil.

A lateritic soil is rich in iron and aluminum, low in silica and chemically acidic. It is usually red or yellow—a reflection of its high iron and/or aluminum content. Laterized soils occur most commonly in the tropical belt between the latitudes of 30 degrees North and 30 degrees South. High temperature and heavy rainfall, at least during part of the year, are basic causes of laterization.

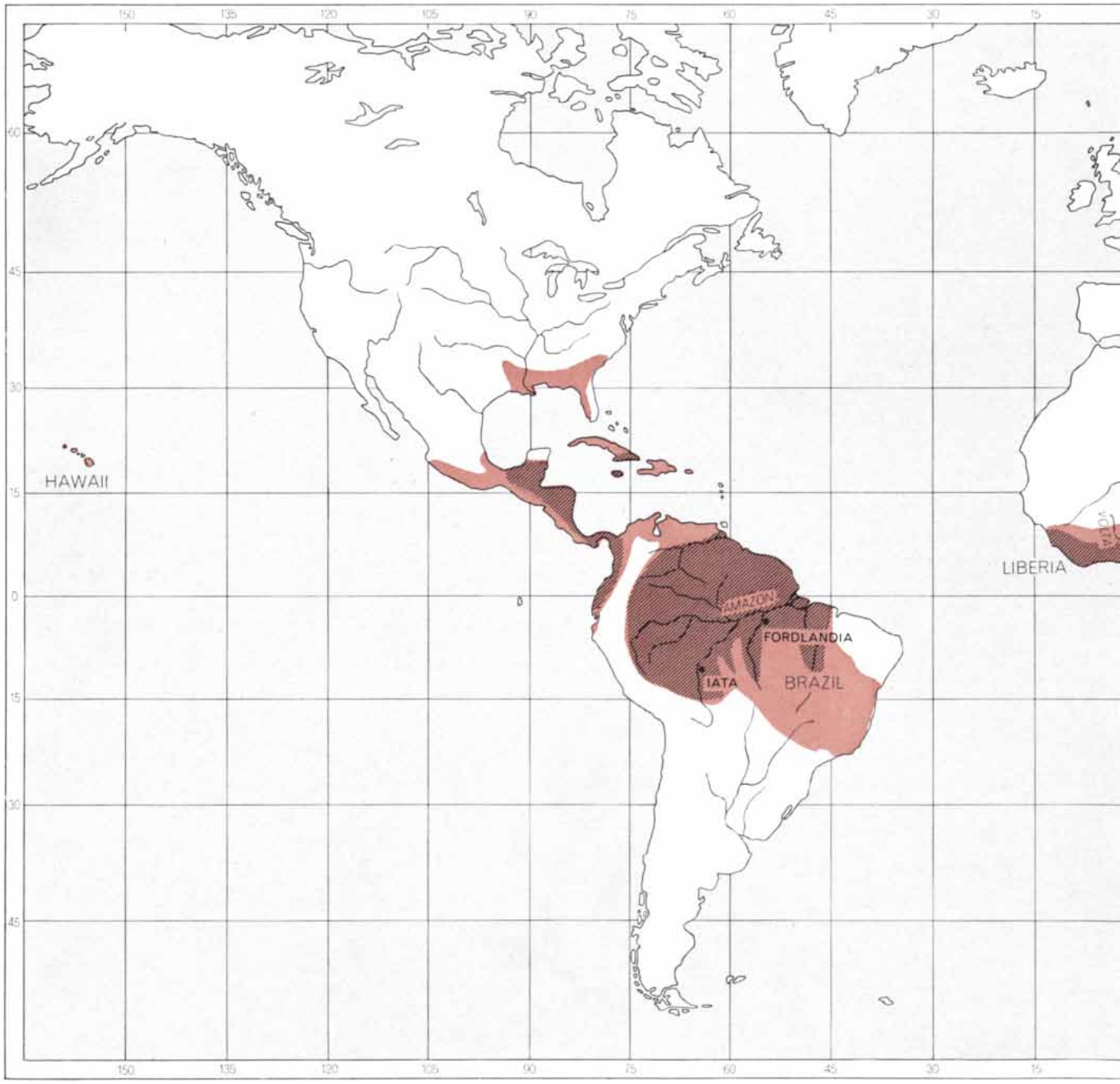
The nature of a lateritic soil can be seen in its profile, or cross section. All soils consist of distinct layers, and soil scientists generally describe them in terms of three main "horizons," labeled *A*, *B* and *C*. In ordinary soils the top layer, horizon *A*, usually contains considerable amounts of organic material, silica, bases and undecomposed minerals; horizon *B* holds an accumulation of material that has leached down from *A*, and horizon *C* is composed of transitional parent rock that is in the process of breaking down into soil through physical and chemical weathering. Lateritic soil shows a radically different picture [*see bottom illustration on page 100*]. Most of the organic material has been broken down and leached out of horizon *A;* the silica and bases also are leached away, and the layer is largely depleted of potassium, calcium, phosphorus and other elements required by plants. The result is that the *A* horizon is composed in large part of oxides of iron, aluminum and other minerals. Below this, the *B* horizon is often either thin or completely missing, and the *C* horizon also may have failed to develop. The soil is so porous that most of the decomposed material has been washed away.

Laterization is a function of the soil climate, which in turn is closely related to the atmospheric climate. The thorough leaching of the soil is primarily due to heavy rainfall, but other tropical conditions play their part. The dampness and high temperature combine to produce a luxuriant growth of bacteria, insects, earthworms and other organisms that break down the organic material and also aerate the soil. The oxygen of the air, permeating this porous soil, oxidizes its iron and aluminum. (It is fortunate that lateriza-

tion is almost entirely limited to the high-rainfall Tropics and even there is held in check by protective vegetation; if it were not, the earth's atmosphere would soon be denuded of oxygen. All the oxygen in the atmosphere would be used up if only a small percentage of the ferrous iron estimated to be in the earth's rocks were oxidized to ferric iron.)

As a result of laterization vast areas of the earth's soil have been converted into deposits of bauxite (aluminum ore) and into hematite and limonite ores of iron. At the same time laterization has also operated to reduce the high-rainfall tropical regions to near-desert conditions from the standpoint of the agricultural quality of their soil. At first thought this generalization may seem unbelievable. Are not the lush jungles, rain forests and savannas of the Tropics plain signs of the fertility of their soil? Actually this lushness is deceptive; it is created only by the abundance of moisture and belies an essential poverty of the soil. Even soil scientists have not found it easy to accept this conclusion, but there is now abundant proof of it. That the tropical forests and grasslands cover some of the earth's most inhospitable and unproductive soils has been demonstrated by attempts to wrest cultivated crops from them. Put to the plow, these lands yield an amazingly small return and soon become completely infertile, as we shall see. Indeed, once a lateritic field has been laid bare to the air, it may even harden into stony laterite such as the brick of the temples of Angkor Thom.

Soil laterization has been taking place

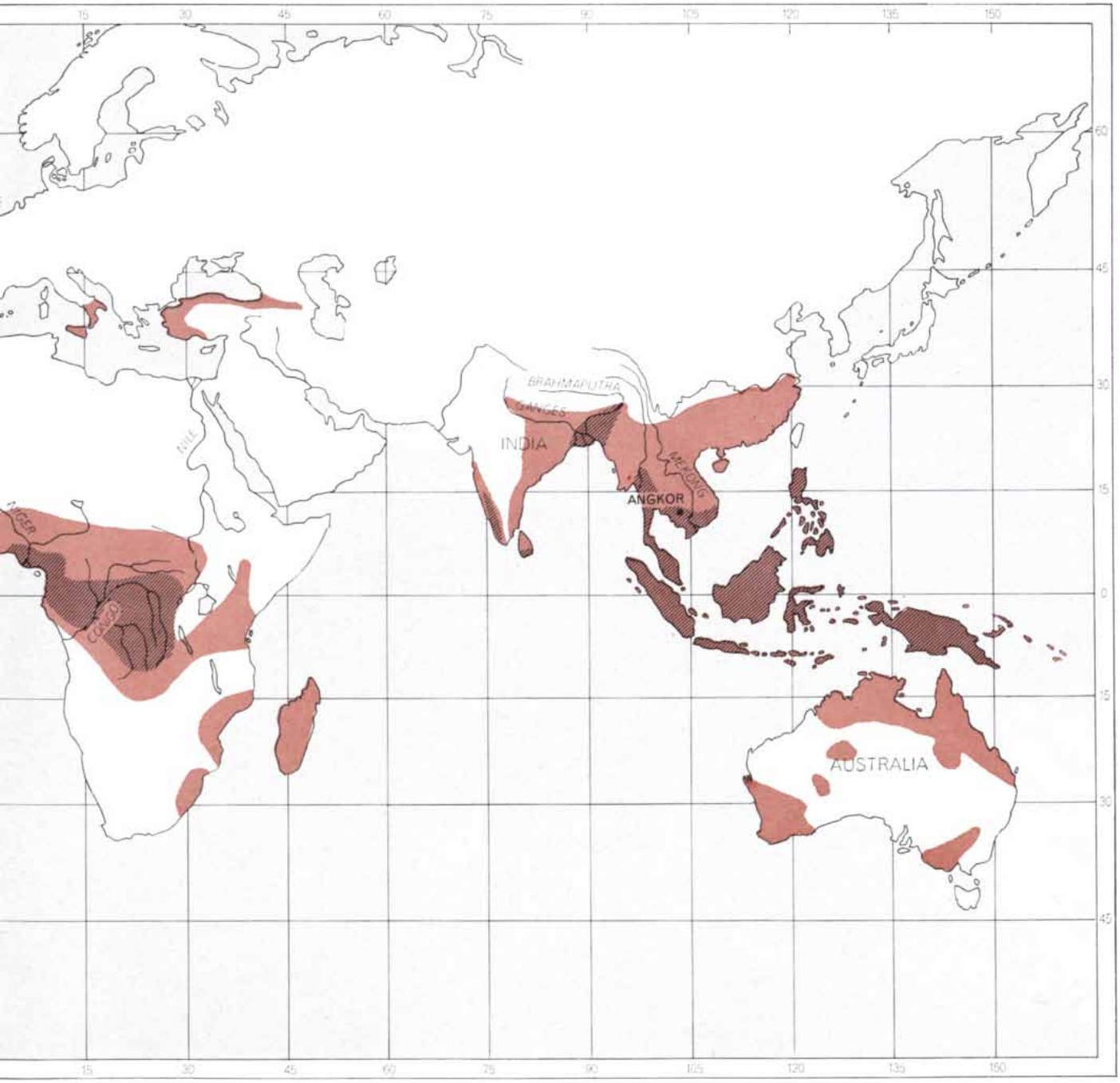


EXTENT OF LATERIZATION is indicated by the colored areas on this map. Laterization is mostly confined to tropical and subtropical regions. Rain forests, shown by hatching, deter hardening of laterite by insulating the soil somewhat from the effects of tropi-

at the earth's surface since the Paleozoic era at least, and probably throughout geologic time. In the Amazon basin of Brazil there are accumulations of lateritic soil 70 feet thick. Deposits such as these are truly fossil soils that provide a record of the soil's various stages of evolution and of the changes in climate, vegetation, topography and geologic processes that took place during their history. In the Brazilian profile we can see all the phases of development of laterite, from its origin as a soil from the parent rock to its final transformation into the vast deposits of bauxite, manganese, iron and new rock that now cover about 1,000 square miles of the basin.

Laterite deposits have been found as far north as Ireland, indicating that it once had a more tropical climate. In many areas of the world—South America, Central America, Africa, Australia, India, southeast Asia—the strata of exposed hillsides show layers of laterite capping various types of underlying rock (igneous, metamorphic and sedimentary). In most cases it looks as if the lateritic soil or laterite once covered a great plain or basin and sections of the deposit were later raised by uplifts of the earth's surface that formed hills and plateaus.

Whatever the details of its history may be, it is clear that the laterization of the soil throughout the tropical belt is still taking place and that the intervention of man now threatens to accelerate the process on a large scale. The ambitious plans to increase food production in the Tropics to meet the pressure of



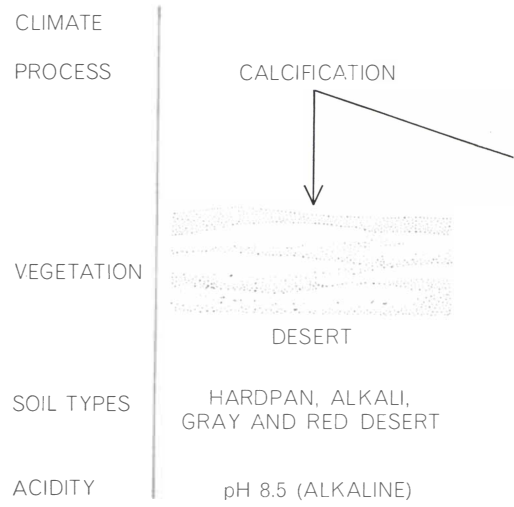
cal climate. Removal of forests, as in efforts to expand agricultural production, tends to quicken laterization, which in turn impairs agriculture. Such an evolution has occurred at Iata in Brazil, where the government undertook to establish an agricultural colony.

the rapid rise in population have given too little consideration to the laterization problem and the measures that will have to be undertaken to overcome it.

In the past nature has provided a measure of control over the process by virtue of forest and jungle growth, which tends to insulate the soil from the eroding effects of the tropical climate and thereby slows down the soil's degeneration. Some of the development plans in underdeveloped areas now call for removing that protective cover to clear the land for agriculture. A recent venture in Brazil vividly illustrates the possible results.

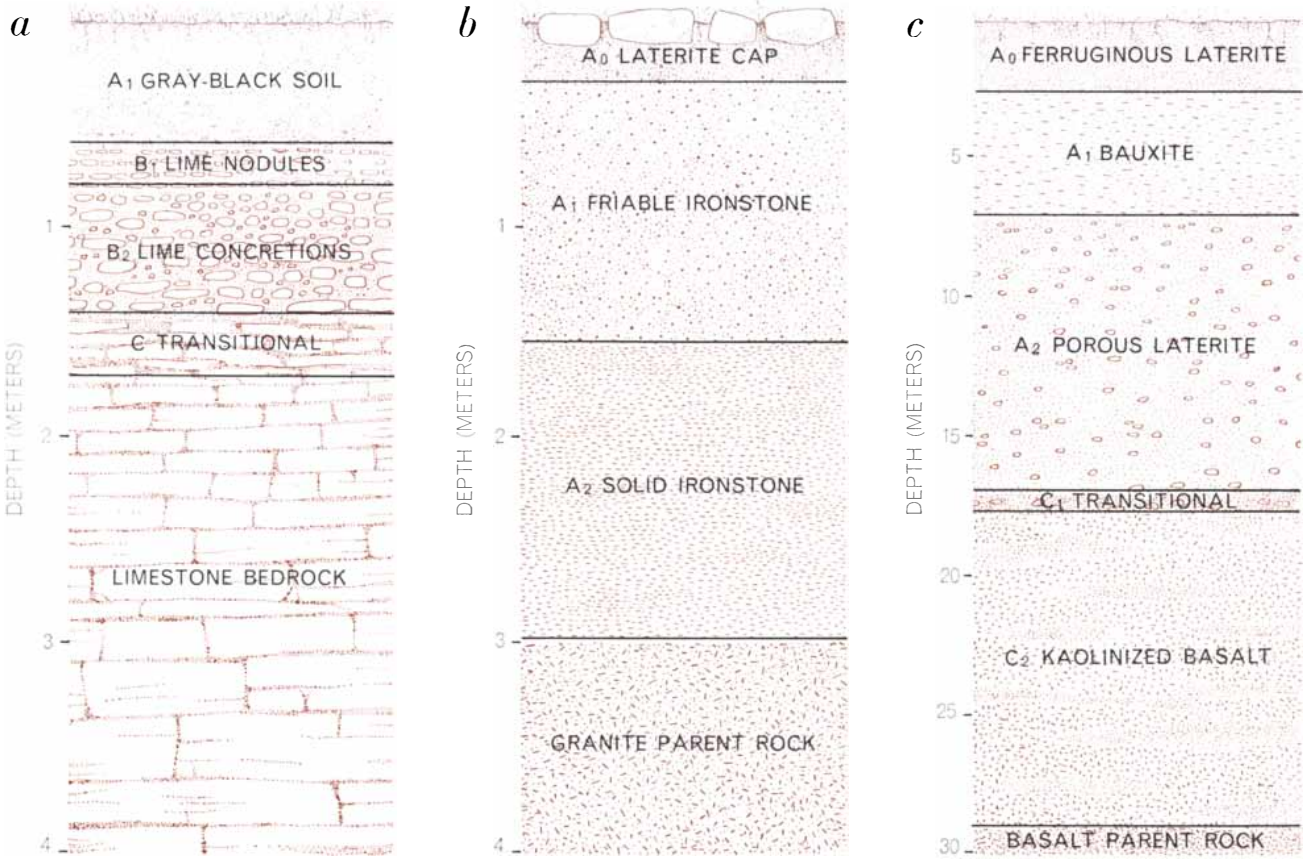
At Iata, an equatorial wonderland in the heart of the Amazon basin, the Brazilian government set up an agricultural colony. Earthmoving machinery wrenched a clearing from the forest and crops were planted. From the beginning there were ominous signs of the presence of laterite. Blocks of ironstone stood out on the surface in some places; in others nodules of the laterite lay just below a thin layer of soil. What had appeared to be a rich soil, with a promising cover of humus, disintegrated after the first or second planting. Under the equatorial sun the iron-rich soil began to bake into brick. In less than five years the cleared fields became virtually pavements of rock. Today Iata is a drab, despairing colony that testifies eloquently to the formidable problem laterite presents throughout the Tropics.

The small country of Dahomey, adjoining Nigeria in tropical West Africa, had a similar experience on a wholesale scale. There the replacement of forests by plantations resulted in deep leaching of the soil and converted large areas into brick in about 60 years. In an equatorial rain forest there is little growth of vegetation on the dark forest floor, and humus fails to accumulate in the soil. Small clearings in such a forest for the "milpa" type of farming, common among forest people all over the world, will exhaust the soil within a year or two. After the clearing is abandoned a jungle-type growth of shrubs, vines and low trees may take over. This happens, however, only where the clearings are comparatively small. Large areas that have been cleared for plantation cultivation are often permanently lost to agriculture after a few crop cycles have worn out the soil.

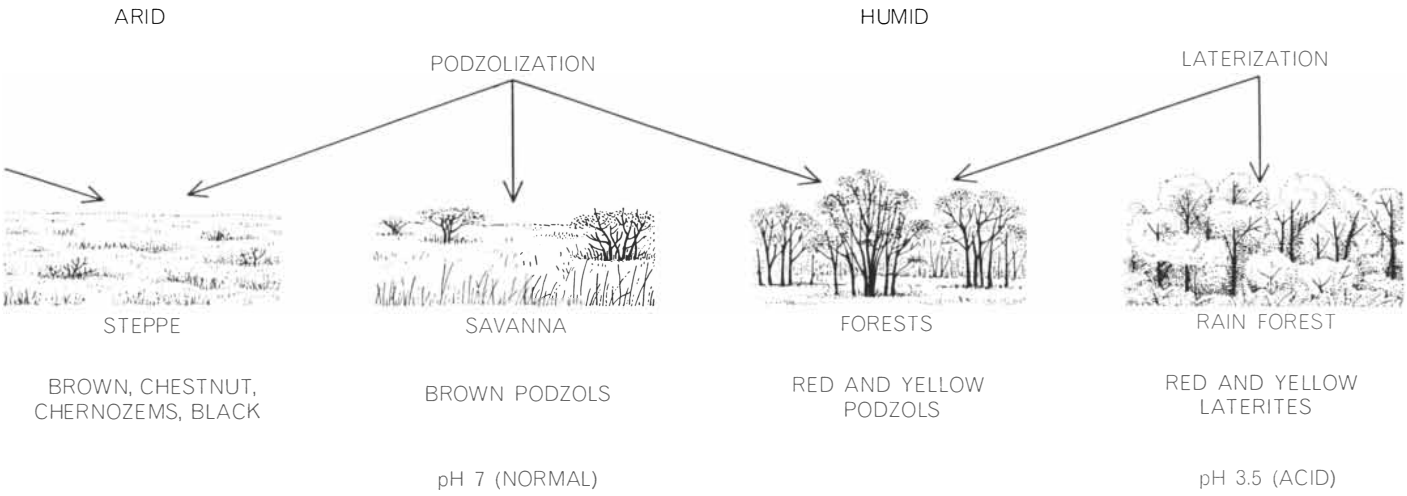


SPECTRUM OF SOILS ranges from dry to wet and alkaline to acidic. The method of formation is indicated by the arrows; the

Going back further in history one can see how important a part laterite must have played in the economies of ancient civilizations in the Tropics. The Khmer civilization in Cambodia may well have perished primarily because of the poverty of the lateritic soil. In



SOIL PROFILES contrast a typical Temperate Zone soil (*a*), as found in northern India, with lateritic soils as found in Dahomey, West Africa (*b*), and in southern India (*c*). Letters at left identify the principal soil horizons, or layers, as usually classified by soil experts. Temperate Zone soils normally have organic material in horizon *A;* in lateritic soils that material has been leached away.



characteristic soil of steppes, for example, is produced through a combination of calcification, which is an accumulation of hardened carbonates, and podzolization, which is a leaching of the upper layers. Lateritic soils usually lack a hardened layer of accumulated carbonates. Weathering under certain conditions of soil climate, which are found in the Tropics, produces lateritic soil.

Central America the Mayas, contemporaries of the Khmers, who depended greatly on the milpa system of agriculture, were forced to abandon their cities and move north into Mexico; perhaps the reason was the low productivity of the lateritic soil in their old kingdom.

In more modern times the British, French and Dutch colonial empires managed to maintain plantation economies in the Tropics by careful attention to the needs of the soil on an empirical basis. From experience their colonial experts learned to provide the necessary fertilizers, to rotate crops and to move the plantations to new sites every few years. Unfortunately, when they gave up their colonies, the experts went home and the newly independent nations were left with few trained people who knew how to deal with the soil. Cuba is a classic example of the necessity for careful and knowledgeable soil management. Long dependent on its great sugar plantations, the island must contend with a lateritic soil of essentially low fertility that will not produce much more than two successive stands of cane on a given tract. The yields of its plantations will steadily decline unless it finds ways to conserve the island's soil.

The advanced nations now concerned with helping the underdeveloped nations of the Tropics must give serious thought to the laterite problem. If Peace Corps workers attempt to apply the agricultural methods of the U.S. corn belt to Nigeria, or Soviet agriculturists transport the methods of the Ukraine to Cuba, they may well precipitate disaster. Deep plowing of the lateritic soil would probably accelerate leaching and strip the soil of all productivity in short order. The opening up of vast tracts to cultivation, in order to make efficient use of tractors and other modern farming machinery, might lead quickly to the baking of these large expanses into brick by exposing the soil to the action of the sun and wind. And the large river-valley plans now projected for many acres—the Mekong River system of southeast Asia, the Amazon basin of Brazil, the Ganges and Brahmaputra valleys of India, the Niger River of Nigeria, the Volta River of Ghana—might lead to devastation of a more subtle kind.

The Mekong Valley has managed, in spite of conditions strongly favoring laterization of the soil, to sustain a productive agriculture: it is part of Asia's famous "rice bowl." The situation must be credited to an act of God, however, rather than to man's efforts. Each year the growing of crops depletes the highly leached soil of this rainy valley. But then in the monsoon season the overflowing rivers of the system flood the land and replenish it with a new layer of silt. Thus nature continues to renew the soil year after year and keep it reasonably fertile. The designers of the Mekong River Plan must now consider what will happen when they stop the annual floods. Plainly they will have to find a substitute for nature's annual replenishment of the soil. The same is true of most of the other tropical river-control projects, in India, Africa, South America and elsewhere.

Nigeria is a particularly good example of the kind of challenge laterite presents. Northern Nigeria, the most densely populated part of the country, is a high plateau; many geologists believe it is a remnant of an uplifted plain that covered most of Africa in Tertiary or early Quaternary times. Much of the Nigerian plateau now contains a cap of laterite, which is covered with a thin veneer of soil in some places and shows outcrops of ironstone in others. Only in the valleys of streams and other eroded beds are there deposits of soil sufficiently fertile to support intensive agriculture. The southern part of Nigeria likewise does not look very promising for the large-scale growing of crops. That area consists mainly of a tropical rain forest that could not be turned into agricultural land without destroying its productivity.

Yet Nigeria will have to depend basically on agricultural exports to raise the capital for the development of industry and a better standard of living. Its main hope seems to lie in control of the Niger River and its delta in such a way that a bed of alluvium will be built up. With careful management and the addition of necessary minerals, the reclaimed land could become a fertile agricultural bowl.

Ghana is even more handicapped agriculturally than Nigeria. Thousands of square miles of its area are covered with an almost continuous sheet of laterite, much of it in the form of bauxite. Like Nigeria, Ghana has a large river, the Volta, which by careful management might produce an arable basin for the growing of food.

Aside from efforts to develop a more arable soil, the tropical forests them-

selves could be exploited more effectively than they have been, in Africa and elsewhere. Several countries have shown that cacao trees (which yield cocoa and chocolate) can be a most profitable crop; the planting of teak in the monsoon forests of Asia has been extraordinarily successful; Fordlandia in Brazil and the Firestone Rubber Company in Liberia are now carrying on experiments on the possibility of developing profitable rubber-tree plantations in the equatorial forests. It has also been urged that the savannas of the Tropics, whose lateritic soils would quickly deteriorate if plowed up for cash crops, could be turned by careful management and fertilization into large ranches and pastures for meat animals.

Laterites are not, of course, an unmitigated evil. In the form of bauxite and other economically exploitable metal ores they are a valuable natural resource. In a world that is increasingly concerned about the problem of feeding the multiplying human population, however, it is time to give intensive consideration to how to prevent the laterization of the soil from becoming a major liability.

A generation ago an American geologist, T. H. Holland, remarked that "laterization might be added to the long list of tropical diseases from which not even the rocks are safe." It is no longer a disease of minor proportions. Nor will this disease be easy to cure. The campaign against it will have to include the mapping of the world's laterized areas, research and experiments in the reclamation of lateritic soils and application of the knowledge that is already available, with the United Nations taking the lead in extending this information and help to the tropical countries. There is no single, simple formula for handling the problem of lateritic soil; each situation has to be studied and treated with an individual prescription. The encouraging fact is that the strategy and technology of agriculture have attained a high level of capability in dealing with difficult problems. What can be accomplished in one such area—where the problem is aridity rather than lateritic soil—is beautifully demonstrated by the flowering of the Negev desert in Israel.

LATERITE CONSTRUCTION appears in the temple of Angkor Wat near Angkor Thom, a major city of the ancient Khmer civilization in what is now Cambodia. Laterite on exposure to air turns into a bricklike form of rock still widely used for construction.

"...EPIDEMIC IMMINENT. NEED SEVEN MILLION DOSES VACCINE IMMEDIATELY. CAN YOU SUPPLY?"

Several years' supply of vaccine needed in a few critical weeks—and don't think it can't happen. Remember the 1947 New York smallpox scare? Seven million doses of vaccine were required. Or the 1958 Asian Flu panic which threatened the whole country. Millions of doses were needed—many times the normal supply. And they were produced, mostly by private industry. There have been infectious hepatitis and polio emergencies, too. And a major concern has always been how to assure an adequate supply of needed drugs on short notice.

One answer turned a large producer of pharmaceuticals into a large consumer of eggs. Researchers at Lederle Laboratories had found a way to shorten the time needed to turn out millions of doses of smallpox vaccine. The eggs served as excellent "breeding grounds" for growing the cultures used in the vaccine.

But there is an equally important problem of "tooling up" for emergency vaccine production. Facilities are needed; so are standby personnel. And because everything must be ready at a moment's notice, almost every large drug company has simply assumed responsibility for emergency production of vaccine as one of its public health functions.

It was, in fact, this very concern for availability that led Dr. Ernst J. Lederle, commissioner of public health of the City of New York, to turn his attention to vaccine production. This was in 1907 when Dr. Lederle's reluctance to depend on foreign sources for diphtheria antitoxin led him to form the company —now a Cyanamid division—that bears his name.

In more recent years, Lederle Laboratories has introduced many new drugs representing significant advances in public health. Typhus vaccine is a pertinent example—the fact that you seldom even hear of the disease nowadays is a tribute to the effectiveness of the vaccine. Antiinfection agents are also vitally important, and Cyanamid was one of the pioneers in the development of sulfa drugs. During World War II, the Company was a major producer not only of sulfa but of tetanus toxoid and typhus vaccines, blood plasma and penicillin. Life-savers like these made World War II the first in history in which disease was less deadly than the enemy.

Peace-time killers are also stalked (as well as being arrested and sometimes executed) by drugs. Good public health in particular demands early detection of disease, and here too Lederle has made some significant advances. Tuberculosis is easier to diagnose today because of the painless Lederle-Rosenthal "tine test" which is cheaper and faster than previous screening methods. So efficient is this test that whole colleges and communities have been screened for TB reactions in a matter of days.

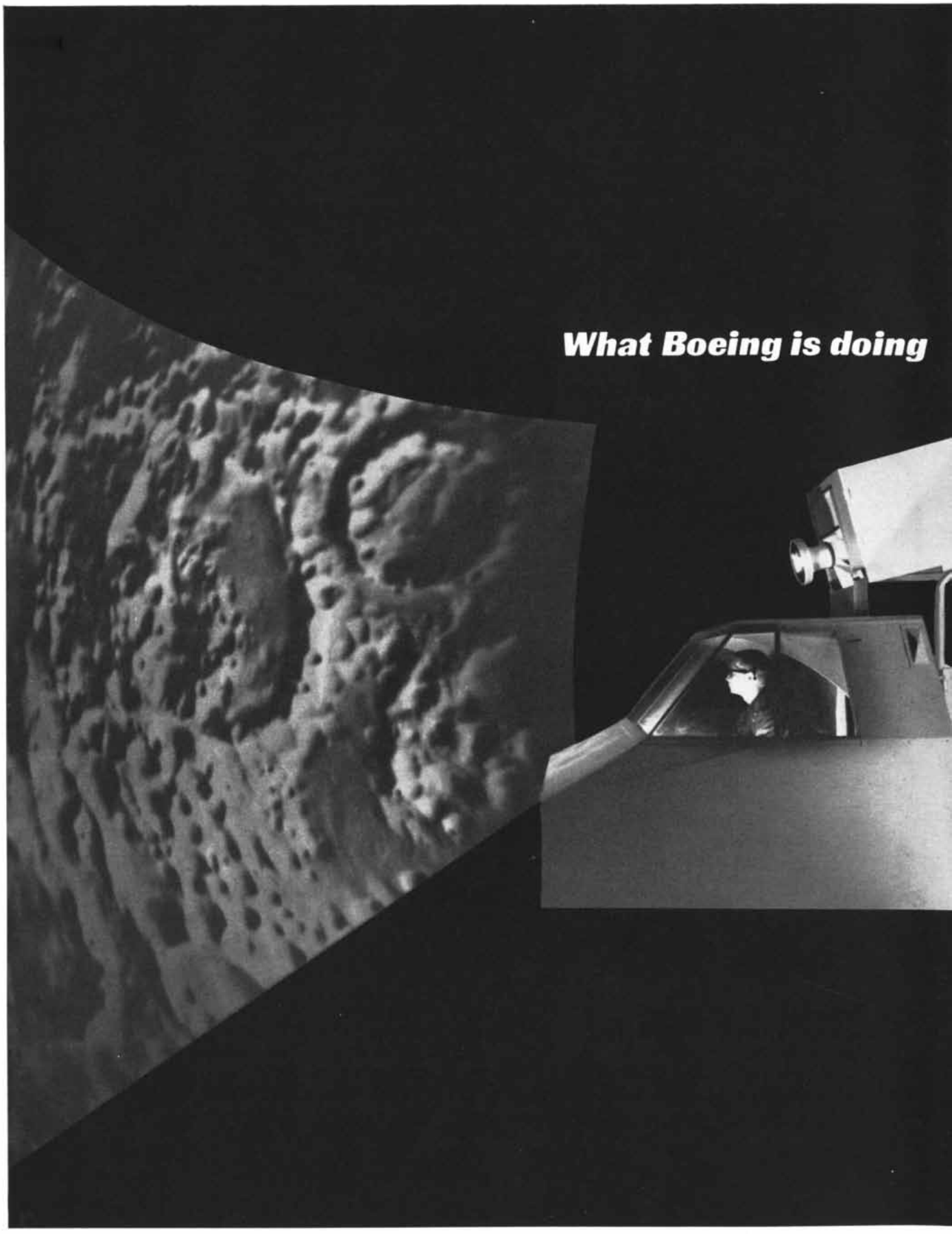
Nor is the Lederle division the only connection Cyanamid has with health and medicine. The company's Davis & Geck division has long been noted for the quality of its surgical supplies. The agricultural division produces a number of veterinary products which help produce more and better meat and which have significantly reduced the number of diseases which animals transmit to man. And other agricultural products protect our grain, fruit and vegetables from the ravages of pests and pestilence.

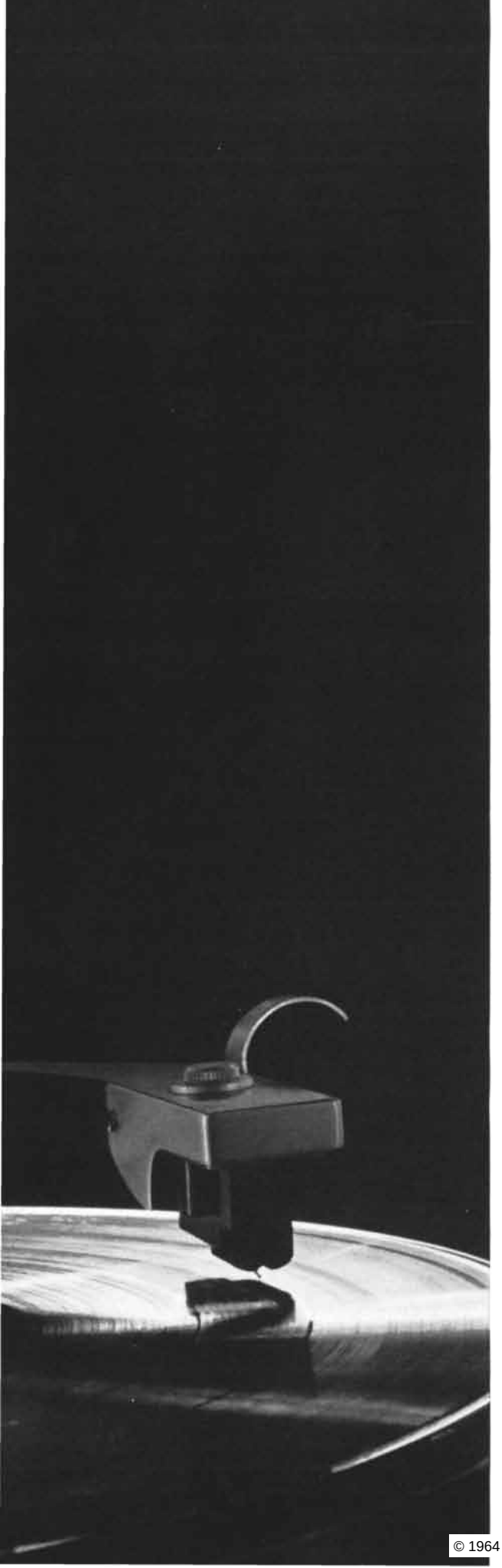
Still, we at American Cyanamid Company feel that Lederle Laboratories has established a quality standard matched by few organizations of any kind anywhere in the world. And for that reason, it is our goal to build into every Cyanamid product the same high degree of effectiveness and protection inherent in every Lederle drug.

CYANAMID

AMERICAN CYANAMID COMPANY
WAYNE, NEW JERSEY

Theory, study, practice...





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

When will it wear out?

Most things we know about—and this includes biological systems—begin to wear out as soon as they go into service. Survival rates do not follow a Gaussian distribution. Life is not symmetrical. For the person concerned with reliability, the problem is to find a realistic mathematical representation of the wear-out phase of components.

In a break from classical reliability statistics, GM Research mathematicians were among the first to use the relatively little known Weibull distribution function . . . a remarkable generalized way of handling skewed distributions by one family of straight lines. To demonstrate its appropriateness, they've developed a number of easy-to-use graphical techniques for planning and interpreting life tests, fatigue experiments, and even incomplete field service data. Among their pioneering contributions:

A new method using median ranks for graphically describing experimental main effects and interactions;

New ways of slashing test times and optimizing experimental designs;

A new method (theory of suspended items) for analyzing endurance data in which some items have failed and some are still running.

Now an accepted standard in the bearing industry, their graphic Weibull techniques have filled numerous papers and two books now on press. It's one of the ways GM researchers and engineers are working to bring improved reliability to both space and earth-bound hardware.

General Motors Research Laboratories

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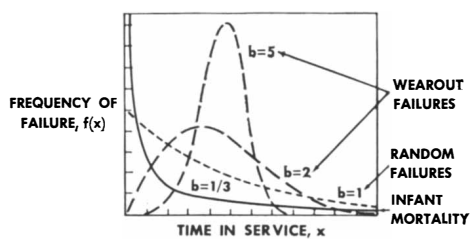


Varying one parameter (b) in the Weibull distribution function allows the characterization of many types of reliability phenomena.

THE MICHELSON-MORLEY EXPERIMENT

Performed in Cleveland in 1887, this famous experiment disproved the hypothesis of a stationary "luminiferous ether." The problems it posed led indirectly to Einstein's special theory of relativity

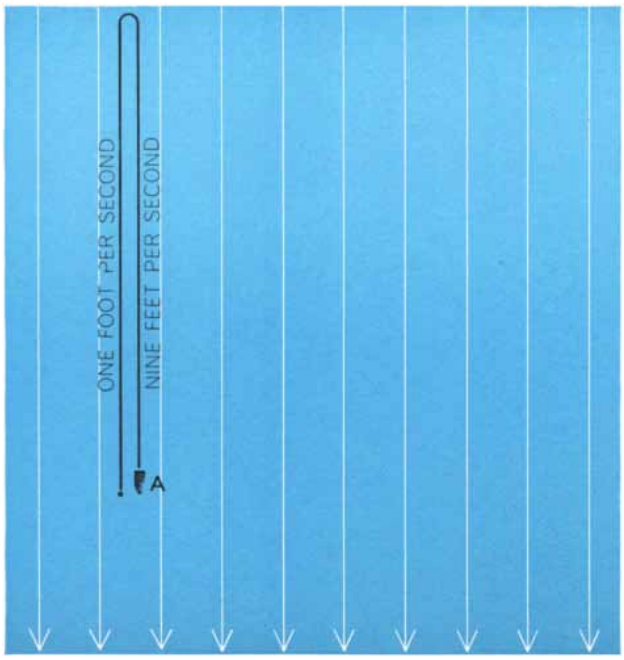
by R. S. Shankland

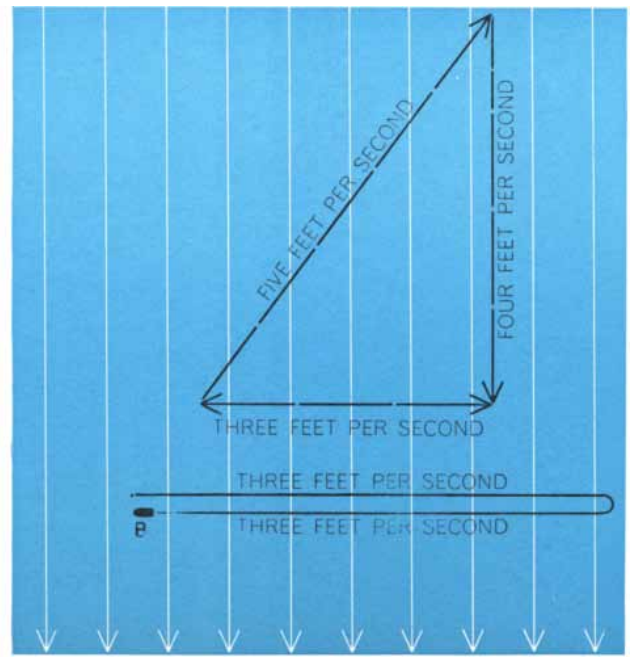
It is widely recognized that the special theory of relativity, introduced by Albert Einstein in 1905, brought about a profound and lasting revolution in man's conception of the physical world. The general theory of relativity, which Einstein developed during the next decade, the relativistic theories of quantum mechanics and quantum electrodynamics, and the most promising hypotheses of modern cosmology are all the lineal descendants of that first, tradition-shattering insight into the true relations of matter, energy, space and time. What is not so well known is the nature of the specific problems Einstein set out to solve in this work. How many people know, for instance, that the paper in which the special theory was first put forward bore the title "The Electrodynamics of Moving Bodies"? For all its theoretical significance, this paper dealt directly with some of the most pressing experimental issues of the time, and it is in the context of these problems that the special theory is perhaps most easily understood.

Nowhere is the close connection between experiment and theory more clearly seen in Einstein's first paper than in its treatment of the problem presented by the relative motion of the earth and the "luminiferous ether," the ubiquitous medium most 19th-century physicists believed to be necessary for the propagation of light waves. This problem had been particularly disconcerting for physicists since 1887, when two Americans, Albert A. Michelson and Edward W. Morley, performed an extremely precise experiment that failed to detect any trace of an "ether wind." The existence of such a wind had been predicted on the assumption that the earth is moving through a stationary ether. As Bertrand Russell has remarked: "The problems solved by the special theory of relativity in its own right, quite apart from the quantum theory, are typified by the Michelson-Morley experiment. Assuming the correctness of Maxwell's theory of electromagnetism there should have been certain discoverable effects of motion through the aether; in fact, there were none." This article will review some of the ideas and events leading up to the Michelson-

ALBERT A. MICHELSON (1852–1931) was 35 years old and professor of physics at the Case School of Applied Science in Cleveland at the time of the decisive "ether drift" experiment in 1887.

EDWARD W. MORLEY (1838–1923) was 49 years old and professor of chemistry at Western Reserve University in 1887, when he joined with Michelson to perform their famous experiment.





ROWBOAT ANALOGY illustrates the principle underlying Michelson's scheme for measuring the motion of the earth through a stationary ether. Rowers *A* and *B* both row at the rate of five feet per second in still water. The stream on which they are rowing flows at four feet per second. Rower *A* (*left*) rows his boat 90 feet upstream and back again to the starting point. Going upstream, he travels at $5-4=1$ foot per second; returning, he makes $5+4=9$ feet per second. His total time is $90/1+90/9=100$ seconds. Rower *B* (*right*) rows his boat 90 feet across the stream and back. His rate of travel can be represented by one of the perpendicular sides of a right triangle whose other perpendicular side is the stream speed and whose hypotenuse is the speed at which he can row in still water. According to the Pythagorean theorem, his actual rate of travel is $5^2-4^2=3$ feet per second. Therefore he takes $90/3=30$ seconds to cross each way and his total time for the trip across the stream and back is only 60 seconds.

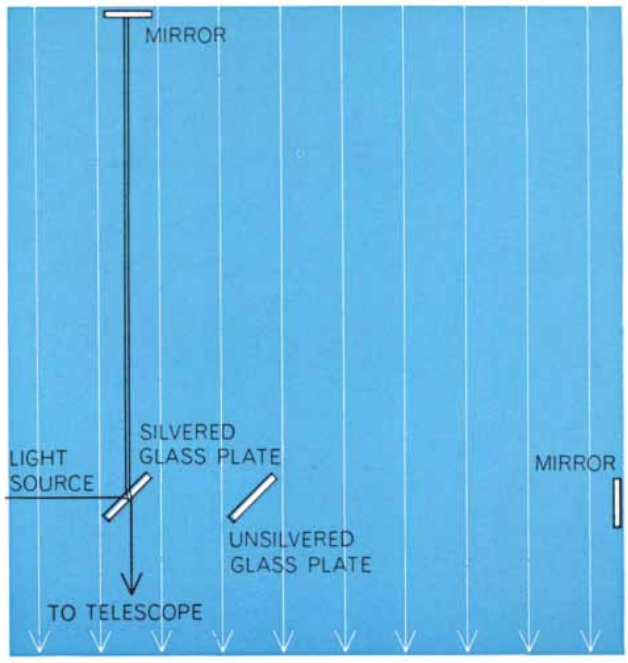
Morley experiment, describe the experiment itself and finally consider its influence on the later development of the theory of relativity.

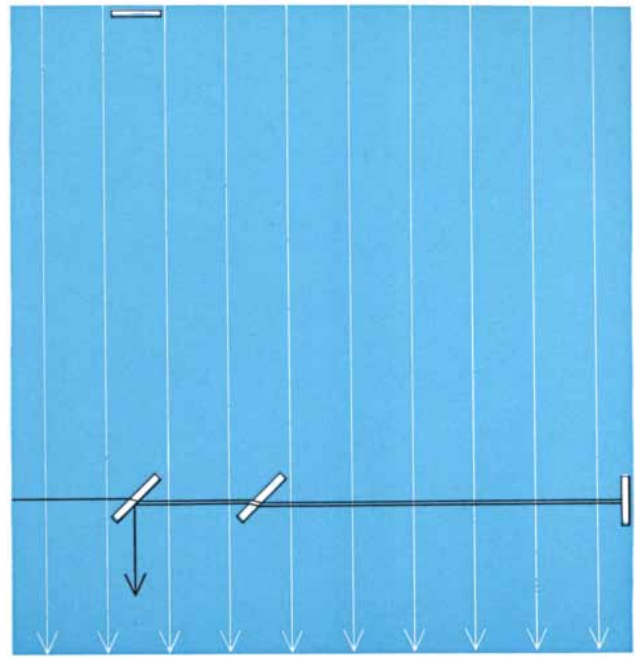
The notion of an ether goes back to the ancient Greek philosophers, including Aristotle, who believed it to be the medium in which the planets and other celestial bodies moved. Although the ether concept was first associated with optical phenomena by Christian Huygens in 1678, it played at best a secondary role in Isaac Newton's corpuscular theory of light; its existence was grudgingly admitted only as a convenient way of avoiding the abhorrent thought of "action at a distance." With the revival of the undulatory, or wave, theory of light in the early 19th century, the concept of a luminiferous, or light-bearing, ether again came into vogue among physicists. By analyzing the ways in which beams of light interfered with each other, Thomas Young of England and Augustin Fresnel of France demonstrated that light must be propagated in continuous waves. Since all other kinds of waves, including sound waves, can be transmitted only in a physical medium, it seemed natural to suppose that light waves would also require some transmitting medium. Unlike sound, however, light can travel through a vacuum—it can travel faster, in fact, than through air or water; hence the light-bearing medium had to be radically different from any known physical substance. In 1818 Fresnel suggested that the ether concept be resurrected to account for the newly discovered wave properties of light.

All through the middle years of the 19th century a great deal of experimental and theoretical work was done in attempts to detect the luminiferous ether and to determine its properties. Among the experiments were various optical and electrical schemes designed to measure the motion of the earth through a stationary ether. All these early experiments failed to come up with any evidence for the existence of the ether, and gradually physicists began to accept the view that although some kind of ether existed it could not be detected by any known laboratory technique.

With the introduction in 1864 of James Clerk Maxwell's celebrated equations demonstrating that light was an electromagnetic phenomenon, a way around this impasse was provided. Implicit in the mathematics of the equations was the prediction that the earth's motion through a stationary ether could be detected by a suitable optical experiment capable of measuring the extremely small but finite quantity represented by the square of the ratio of the earth's orbital speed to the speed of light; in symbols the quantity is $(v/c)^2$. At the time Maxwell regarded such an experiment as purely hypothetical, since the sensitivity required to detect so minute an effect was about one part in 100 million and no known optical measurement could approach this sensitivity.

Working at the Nautical Almanac Office in Washington, D.C., however, was a young naval officer with a special gift for precise optical measurements. In 1873, at the age of 21, Albert A. Michelson had performed an ingenious experiment that had yielded the most accurate measurement of the speed of light up to that time: 299,853 kilometers per second (the best modern figure is 299,793 kilometers per second). Michelson's interest in the experiment suggested by Maxwell was kindled in the spring of 1879, when he had an opportunity to read a letter Maxwell had written to David Peck Todd, a colleague of Michelson's at the Nautical Almanac Office. In this letter Maxwell had asked if the existing data on the eclipses of Jupiter's moons was





MICHELSON'S SCHEME for measuring the motion of the earth through a stationary ether consisted essentially in dispatching two beams of light from the same source in two mutually perpendicular directions but for equal distances, reflecting both back to a common point and measuring what difference, if any, there was between the two arrival times. If an "ether wind" existed, one of the two light beams would have to travel upwind and back (*left*) and thus arrive slightly later than the beam traveling across the wind and back (*right*). In Michelson's first interferometer the original beam was split into two components at the thinly silvered back surface of a partially transmitting and partially reflecting plate of silvered glass. A second, unsilvered plate was placed in the path of one of the component beams so that each beam would pass through three equal thicknesses of glass. The beams were reunited at silvered plate and directed into a small telescope, where their interference effects could be observed.

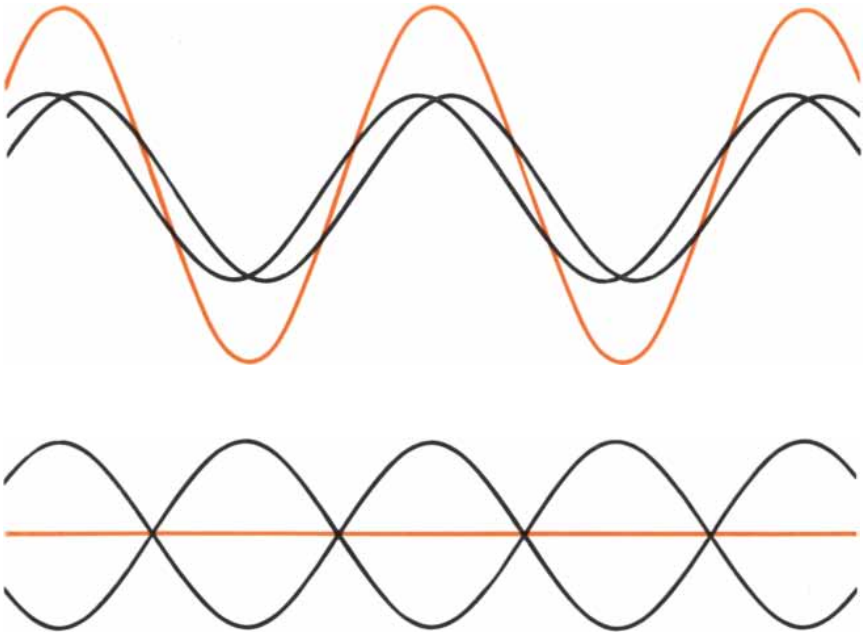
accurate enough to provide the basis for an optical experiment aimed at determining the motion of the earth through the ether. (The earliest measurement of the speed of light, made by the Danish astronomer Ole Roemer in 1676, was based on the periodic delay observed in the eclipses of Jupiter's moons owing to the rotation of the earth around the sun.)

The part of Maxwell's letter that particularly attracted Michelson's attention was the statement in the final paragraph that "in all terrestrial methods of determining the velocity of light, the light comes back along the same path again, so that the velocity of the earth with respect to the aether would alter the time of the double passage by a quantity depending on the square of the ratio of the earth's velocity to that of light, and this is quite too small to be observed."

In this statement Michelson saw the germ of an experimental technique that would enable him to measure to the required accuracy the quantity Maxwell considered "quite too small to be observed." In essence Michelson's plan was remarkably simple. He would dispatch two beams of light from the same source in two mutually perpendicular directions but for equal distances, reflect both back to a common point and measure what difference, if any, there was between the two arrival times. The principle behind this technique is best illustrated by a familiar analogy. Personal experience or a little arithmetic will show that it takes longer to row a boat a given distance at a given rate upstream and back again to the starting point than it does to row the same distance at the same rate directly across the stream and back again [*see illustration on opposite page*]. By the same token, if an ether wind existed, one of the two light beams would have to travel upwind and back and thus arrive slightly later than the beam traveling across the wind and back [*see illustration above*].

Obviously the problem resolved itself into one of measuring the extremely small interval between the two arrival times. For this task Michelson took advantage of the phenomenon of optical interference [*see top illustration on next page*]. If the two reunited light beams take equal times for their journeys, their waves will arrive in step and will reinforce each other. If the travel times are unequal, however, the light waves will be out of step and will interfere with each other. In the latter case the interfering waves can form a pattern of alternating dark and bright regions, called interference fringes, on any interposed surface [*see bottom illustration on next page*]. A very small change in the interval between the two arrival times will result in a corresponding shift in the pattern of interference fringes; since a lag of one wavelength between the two beams corresponds to a shift of one full interference fringe, this technique provided an extremely sensitive means for measuring the minute interval between the two arrival times. Putting this principle into practice was to require the greater part of Michelson's time and labor for the next eight years.

In 1880 Michelson was granted a two-year leave of absence by the Navy to study optical techniques in Europe, and he immediately began work on his proposed apparatus for measuring the optical effect of the earth's motion through the ether. It was in the laboratory of Hermann von Helmholtz at the University of Berlin that he set up the first version of the instrument that has come to be known as the Michelson interferometer. In this device a beam of light was directed at a partially transmitting and partially reflecting plate of silvered glass. The beam was split into two components at the thinly silvered



INTERFERENCE OF LIGHT WAVES was taken advantage of by Michelson to measure the extremely small interval between the two arrival times of the reunited light beams in his interferometer. If the waves are in step or only slightly out of step (*top*), wave crests will meet and reinforce each other, producing an increase in the intensity of the light (*colored line at top*). If the waves are exactly one-half wavelength out of step (*bottom*), wave crests will meet wave troughs and cancel each other, producing no light (*colored line at bottom*).

INTERFERENCE FRINGES are produced when any surface is interposed in the path of interfering light waves. This photograph was made by the author through the telescope of a Michelson interferometer. A very small change in the interval between arrival times of the two light beams will result in a corresponding shift in pattern of interference fringes.

back surface of the glass; the two components thus formed were made to travel at right angles to each other to two mirrors placed at equal distances from the silvered plate. The mirrors reflected the beams back to the silvered plate, where they were reunited and directed into a small telescope in which the effects of their interference could be observed. The optical parts of this first interferometer were fixed to a laboratory pier by pieces of wax and the adjustments were comparatively crude; it took hours of work just to find the interference fringes in the telescope.

Shortly thereafter a more sensitive interferometer was constructed for Michelson by a Berlin instrument-maker with funds supplied by Alexander Graham Bell. It was with this instrument that the first "ether drift" experiments were performed in Berlin and at the Astrophysical Observatory in Potsdam in 1881. Unfortunately the optical parts of the instrument were mounted on two arms that were not rigid enough to keep the interference fringes from moving when the interferometer was turned on its axis. Hence mechanical strains and distortions caused by the traffic outside Helmholtz' Berlin laboratory made the interference fringes unsteady and often caused them to move as much as or more than the anticipated shift due to the ether drift. Slightly better conditions were attained at Potsdam, but the results were unsatisfactory, and Michelson himself never considered them reliable. He did publish his findings, however, concluding that "the interpretation of these results is that there is no displacement of the interference bands. The result of the hypothesis of a stationary ether is thus shown to be incorrect."

The scientific world never regarded the results of the Potsdam experiment as conclusive evidence against an ether, although Lord Rayleigh and Lord Kelvin (then Sir William Thomson) in Britain, and H. A. Lorentz and others on the Continent, gave them careful and respectful attention. Michelson himself was keenly disappointed with the experiment. He abandoned this line of research and returned to his investigation of the speed of light. For many years he referred to the Potsdam experiment as a failure. It seems certain that he would never have returned to the ether-drift experiment if it had not been for a series of events that occurred after he resigned his Navy commission later in 1881 to become the first professor of physics at the newly organized

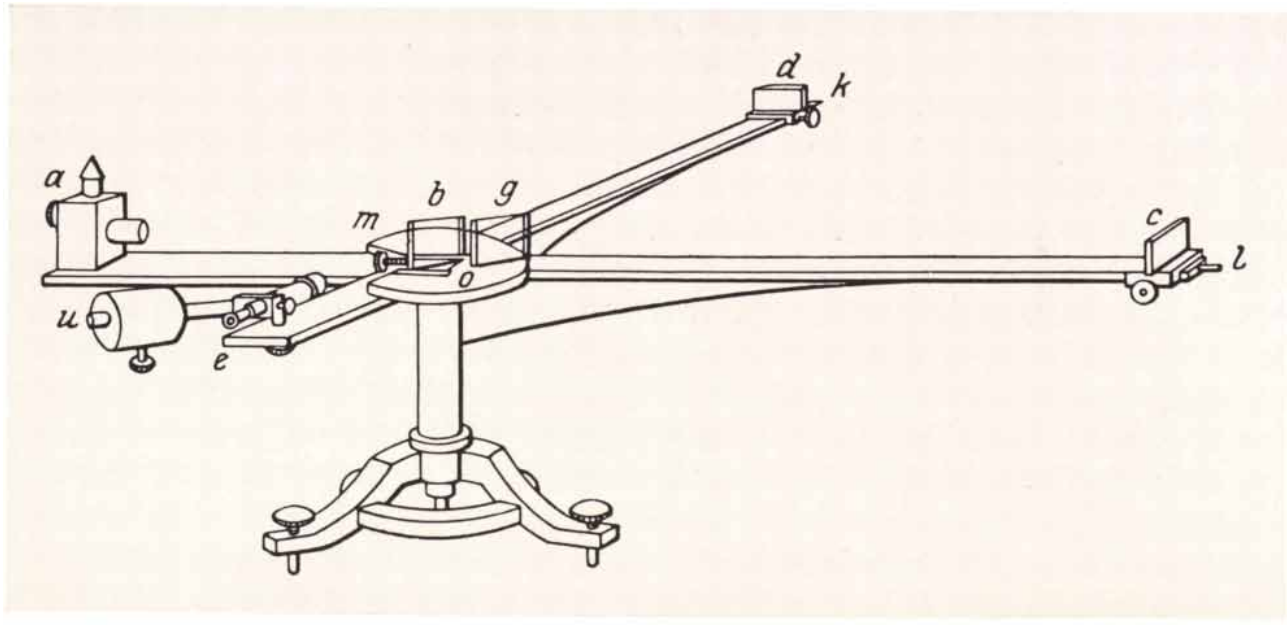
Case School of Applied Science (now the Case Institute of Technology) in Cleveland. There he met Edward W. Morley of the neighboring Western Reserve University. Morley not only was a leading chemist but also was accomplished in both mathematics and physics. Michelson and Morley became close friends, and their collaboration in various projects led to the decisive ether-drift experiment that bears their names.

The joint interest of Michelson and Morley in the ether-drift problem was stimulated by the urging of Lord Kelvin and Lord Rayleigh at the time of Kelvin's Baltimore lectures in 1884. In October of that year Kelvin had come to Baltimore to give a series of lectures at Johns Hopkins University entitled "Molecular Dynamics and the Wave Theory of Light," which took up the problem of the luminiferous ether. Michelson and Morley attended these lectures, as did most of the foremost U.S. physicists of the day. Both in his lectures and in conversations afterward Kelvin discussed the Potsdam experiment and urged Michelson to give his interferometer work another trial. Morley was also drawn into these conversations; it appears that the encouragement Kelvin and Rayleigh gave Michelson and Morley was decisive in their resolution to give the ether-drift experiment a more thorough test.

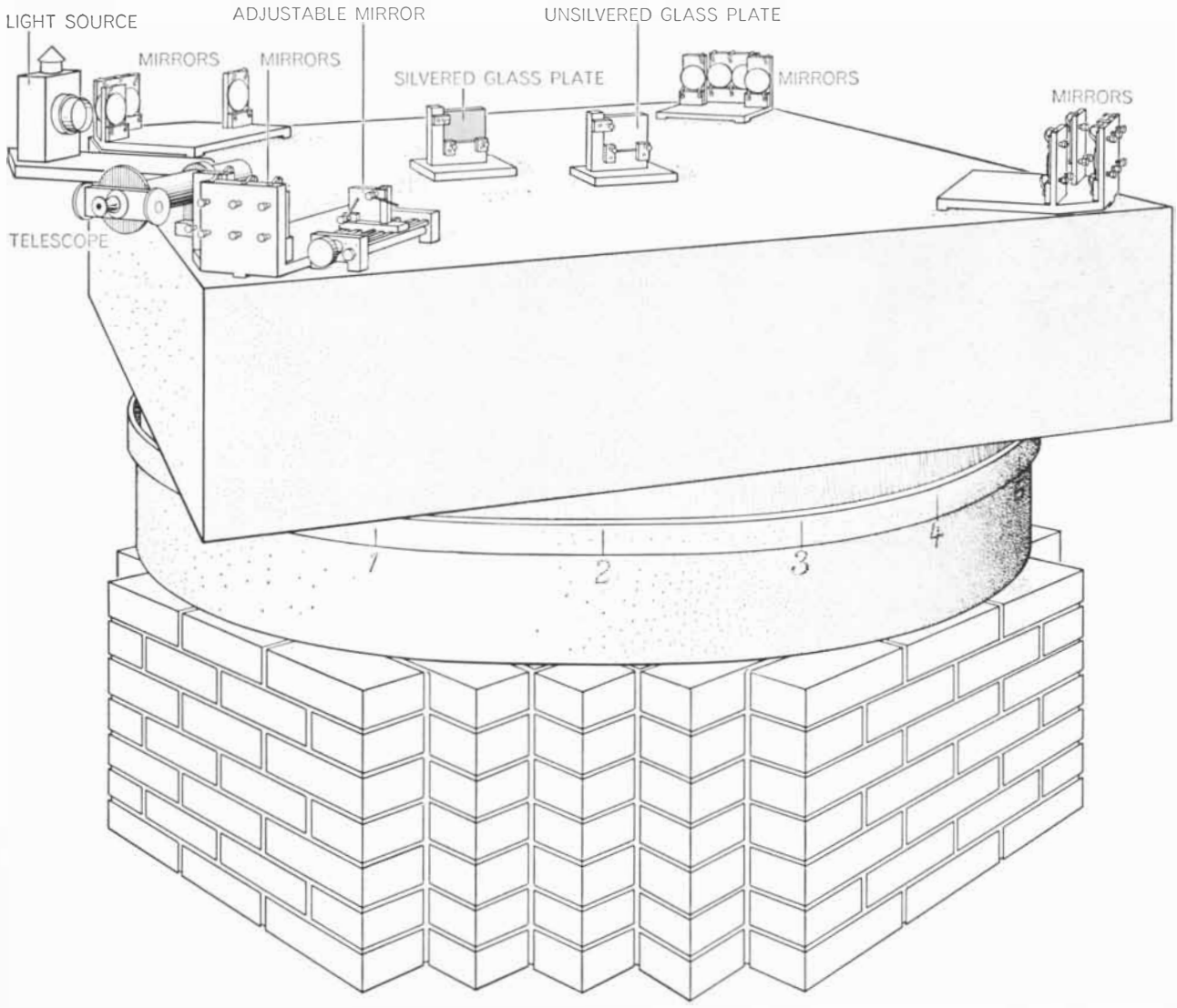
When Michelson and Morley returned from Baltimore to Cleveland, they immediately began their researches into the ether-drift problem. An important preliminary to their main experiment was the repetition of an experiment undertaken by the French physicist Hippolyte Fizeau in 1851 to measure the speed of light in moving water. Fizeau's measurement had had an important influence on the development of the wave theory of light and on the problem of the motion of the earth through the ether. Lorentz had shown that if Fizeau's result was in error, this might explain the negative result observed by Michelson at Potsdam. In any case the Fizeau experiment was important for the whole ether-drift problem, and a better measurement would be of value. Furthermore, by improving on the Fizeau experiment Michelson and Morley would gain experience in optical-interference methods and develop the techniques they would need later in their own experiment. Michelson was particularly eager to repeat the experiment because a definite quantity would be measured; he always favored experiments that gave numbers. Even after the Michelson-Morley experiment had made him famous he was not keenly interested in it, because the result did not represent an actual measurement.

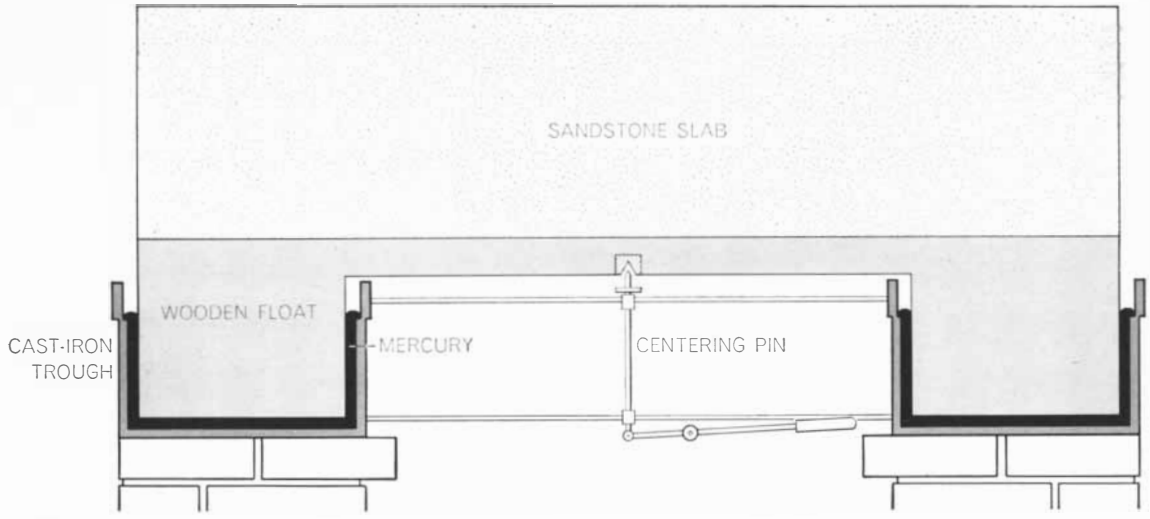
When their much more precise repetition of the Fizeau experiment confirmed Fizeau's observations, Michelson and Morley turned their energies to the design and construction of an improved ether-drift interferometer. Morley suggested mounting the optical parts on a stone slab and floating the slab in mercury; this would lessen the strains and vibrations that had so affected the interferometer used at Berlin and Potsdam. In the final design a sandstone slab five feet square was mounted on a doughnut-shaped wooden float, which in turn was placed in a similarly shaped cast-iron trough filled with mercury [*see illustration on next page*]. One advantage of the design was that only a comparatively small amount of mercury was needed to support the heavy stone slab. The arrangement also made it possible to continuously rotate the interferometer in the horizontal plane, so that observations of the interference fringes could be made in all directions. When the interferometer was set in motion, it would rotate slowly (about once every six minutes) and for hours at a time. No starting and stopping was necessary, and the motion was so slow that accurate readings of the fringe positions could be made as the apparatus turned.

Another improvement on the basic design followed by Michelson in Germany involved lengthening the flight paths of the two perpendicular light beams. By using four mirrors instead of one at each end of both flight paths the beams could be reflected back and forth several times; this increased the effective length of the arms of the ap-



INTERFEROMETER used by Michelson in his unsuccessful ether-drift experiments in Germany in 1881 appears in this contemporary drawing. Optical parts of the instrument were mounted on two arms that were not rigid enough to prevent the interference fringes from moving when the interferometer was turned on its axis. Berlin traffic also produced vibrations in the instrument.





MICHELSON-MORLEY APPARATUS used in decisive ether-drift experiment in Cleveland in 1887 incorporated several important improvements over the earlier Michelson interferometers. Optical parts were mounted on a sandstone slab five feet square, which was floated in mercury, thereby reducing the strains and vibrations that had so affected the earlier experiments. The stone itself was mounted on a doughnut-shaped wooden float, which in turn was placed in a similarly shaped cast-iron trough filled with mercury (*see cutaway view at bottom*). Observations could be made in all directions by rotating apparatus in horizontal plane.

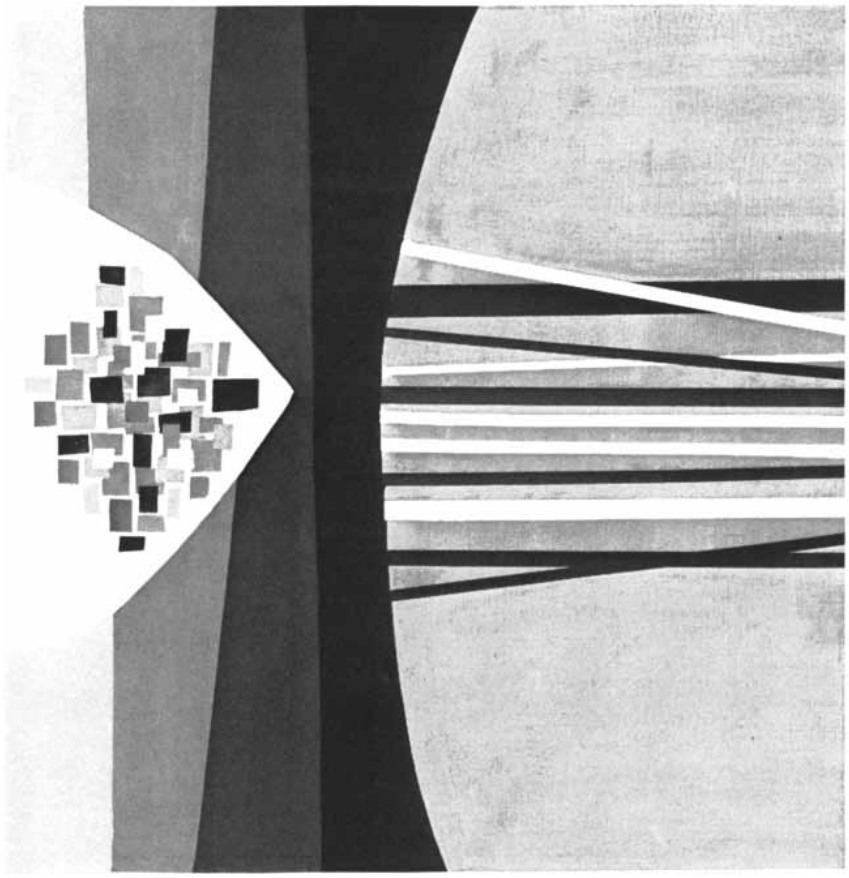
paratus from slightly less than four to more than 36 feet [*see illustration on next page*]. The increase in the length of the flight paths made the apparatus nearly 10 times more sensitive than the Potsdam design.

For an instrument of this sensitivity the shift in the interference pattern that would be caused by the earth's motion through an ether would be four-tenths of a fringe as the instrument was rotated through an angle of 90 degrees. (For an instrument with the sensitivity of the Potsdam design the shift would have been only four-hundredths of a fringe.) From their recent repetition of the Fizeau experiment Michelson and Morley felt confident that fringe shifts of this order of magnitude could be measured with great precision.

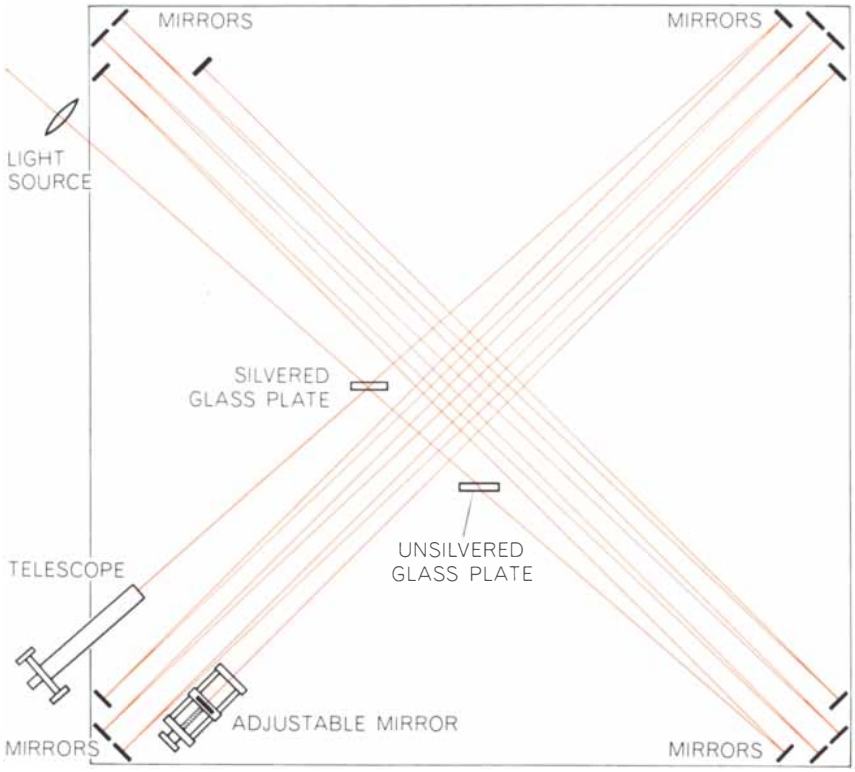
The construction and testing of the new interferometer took the better part of two years. These efforts were seriously hampered in the fall of 1886 by a fire that destroyed the Case Main Building, where the Michelson-Morley apparatus had been set up. Fortunately most of the equipment was rescued from the fire by students, and the experiment was transferred to a nearby building at Western Reserve.

Michelson and Morley had originally planned to make observations during each month throughout an entire year, so that every stage of the earth's motion through space would be included in the experiment. In this way any fortuitous cancellation of the earth's motion around the sun by the velocity of the entire solar system through space would be revealed. Finally in July, 1887, the two men were ready to give their experiment its crucial trial. The observations that yielded their published results were made at noon and in the evening of July 8, 9, 11 and 12. The interferometer was set rotating in the mercury and the positions of the interference fringes were observed in all directions. According to the ether hypothesis, the fringes should have moved considerably during each rotation of the interferometer. Instead of the expected shift of four-tenths of a fringe, however, Michelson and Morley found "that if there is any displacement due to the relative motion of the earth and the luminiferous ether, this cannot be much greater than .01 of the distance between the fringes."

It was no longer possible to believe that a positive result might be hidden in the errors of observation, and the doubts that had hung over Michelson's



Interpretation by William Thonson



VERTICAL OVERHEAD VIEW of the Michelson-Morley apparatus depicted on page 112 shows the arrangement of the flight paths of the two perpendicular light beams. By using four mirrors instead of one at each end of both flight paths the beams could be reflected back and forth several times; this increased the effective length of the arms from less than four to more than 36 feet, making apparatus 10 times more sensitive than earlier versions.

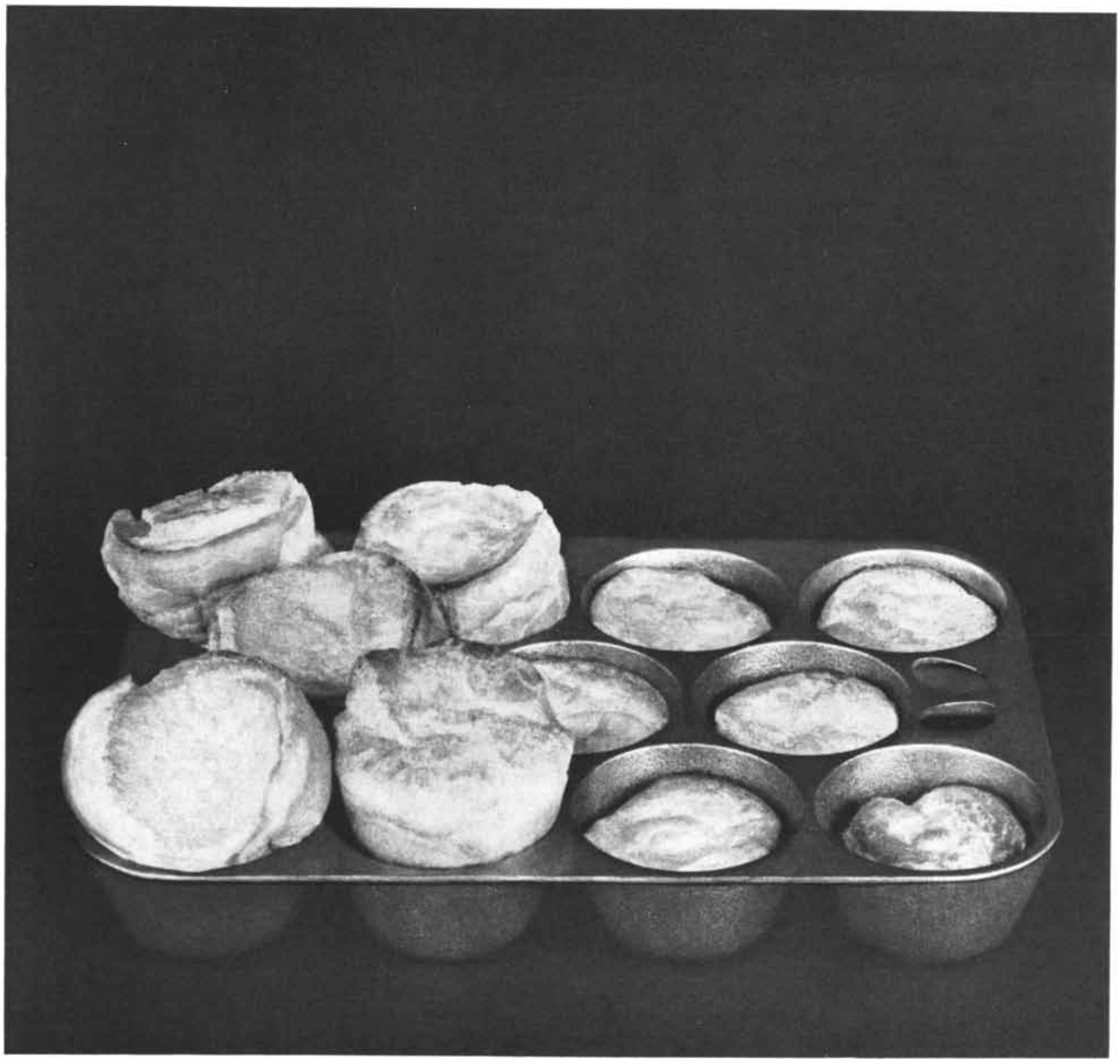
Potsdam experiment were now entirely dispelled. All explanations that had attempted to reconcile the Potsdam result with existing theories now had to be abandoned, and new theoretical explanations for the behavior of moving optical and electrical systems had to be found. Nonetheless, some of the chief proponents of the older theories, including Kelvin and Rayleigh, hoped that there might be some point in the theory of the Cleveland experiment that had been overlooked, and that further analysis of the 1887 result might still permit the ether hypothesis to be retained. As late as 1900, at the International Physics Congress in Paris, Kelvin urged Morley and Dayton C. Miller of the Case Institute to repeat the experiment with greater precision; they did so in 1904 with greatly improved apparatus and obtained an even more conclusive negative result than the one obtained by Michelson and Morley.

The theoretical dilemma presented by the result of the Michelson-Morley experiment provoked several new and rather arbitrary hypotheses to explain it. The most curious of these was advanced by the Irish physicist G. F. FitzGerald, who suggested in 1892 that the dimensions of the Michelson-Morley apparatus might have contracted in the direction of its motion through the ether by an amount that depended on its velocity. According to FitzGerald this amount would be just enough to account for the negative result of the experiment. In working out a quantitative physical model of FitzGerald's contraction hypothesis Lorentz developed several new mathematical techniques (called Lorentz transformations) that were to play an essential role in Einstein's special theory of relativity. The contraction hypothesis itself was also incorporated (in a slightly different form) in Einstein's theory.

In 1899 Henri Poincaré of France proposed that the result of the Michelson-Morley experiment be generalized into a doctrine that absolute motion is in principle not detectable by laboratory experiments of any kind. To describe this generalization he suggested the term "principle of relativity." Poincaré also concluded that "there must arise an entirely new kind of dynamics, which will be characterized above all by the rule that no velocity can exceed the velocity of light." The most remarkable fact about the obvious similarities between these ideas and the later postulates of Einstein's special theory is that Einstein was apparently unaware of Poincaré's work and arrived at more or less the same conclusions independently.

Instead of trying to modify the older theories and adapt them to the new experimental facts, Einstein struck out in an entirely new direction. He adopted two postulates on which to base his theory. The first was the principle of relativity, which Poincaré had already shown was inherent in the results of the Michelson-Morley experiment. This postulate assumed the impossibility of detecting absolute uniform motion of any body by a laboratory experiment. The second postulate stated that the speed of light in empty space is a universal constant and is not influenced in any way by the motion of the light source or the observer. This postulate was a bold step, only partly supported by experimental fact, and is perhaps Einstein's most original contribution to the problem. Among other things, Einstein's approach made the concept of an ether superfluous and provided an acceptable explanation for the negative result of the Michelson-Morley experiment.

In a statement sent to the author in 1952 on the occasion of a special meeting of the Cleveland Physics Society honoring the centenary of Michelson's birth, Einstein acknowledged his debt to Michelson and Morley: "The influence of the crucial Michelson-Morley experiment upon my own efforts has been rather indirect. I learned of it through H. A. Lorentz' decisive investigation of the electrodynamics of moving bodies, with which I was acquainted before developing the special theory of relativity. Lorentz' basic assumption of an ether at rest seemed to me not convincing in itself and also for the reason that it was leading to an interpretation of the result of the Michelson-Morley experiment which seemed to me artificial. What led me more or less directly to the special theory of relativity was the conviction that the electromotive force acting on a body in motion in a magnetic field was nothing else but an electric field.... There is, of course, no logical way leading to the establishment of a theory but only groping constructive attempts controlled by careful consideration of factual knowledge."



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PSYCHOLOGICAL TIME

Everyone knows that his subjective sense of the passage of time can be influenced by circumstances. How much various circumstances affect this sense is explored by experiment

by John Cohen

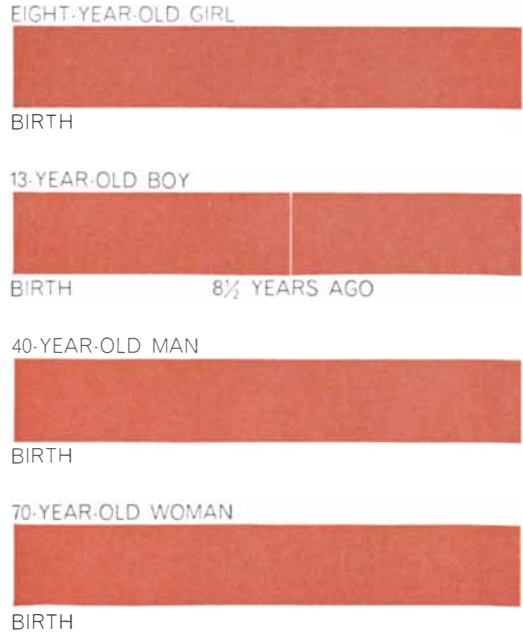
"The mind of man works with strangeness upon the body of time," Virginia Woolf wrote in *Orlando*. "An hour, once it lodges in the queer element of the human spirit, may be stretched to fifty or a hundred times its clock length; on the other hand, an hour may be accurately represented by the timepiece of the mind by one second." A typical example of this "strangeness" is that half an hour under a dentist's drill seems far longer than half an hour spent golfing. Equally familiar is the experience that the years seem to pass much more quickly in adulthood than in childhood. Both kinds of experience are aspects of psychological time: the subjective time that for each person is more or less independent of objective time.

Psychological time has many other aspects. One is the tendency of the individual's view of past events to change with the passage of years. Another is that conceptions of time differ between one nation or culture and another. I might also mention the habit of regarding time as a personal possession: one can "give" of one's time or "waste" it or "save" it—an attitude that calls to mind the rioting that occurred in England when the Gregorian calendar was adopted and September 3, 1752, became September 14, leading many people to insist that they had "lost" 11 days. Finally I might recall man's ceaseless struggle to arrest the flow of time because he recognizes the inevitability of aging and carries the foreknowledge of death. Evidence of this struggle can be found in the ancient practice of equipping the dead with food and weapons for the continuation of life, in the attempt by Pope Innocent III to rejuvenate himself by transfusing the blood of three young men into his veins, and even today in the efforts of cosmeticians and morticians. Each of these features could be considered at length. In this article, however, I shall confine myself to four aspects of psychological time, first considering some historical attitudes toward time, then dealing with "biological clocks" as they are related to psychological time, thirdly describing how people estimate intervals of time, and finally discussing orientations toward the future.

In antiquity men regarded time as expressing power, opportunity and plenitude. A typical representation equating time with opportunity is the Greek bas-relief entitled "Kairos," now in the Turin Museum: it shows a man with wings on his shoulders and feet carrying scales balanced on a knife-edge; also shown are the wheel of fortune and a forelock by which opportunity could be seized. An Iranian representation is Aion, a symbol of eternal and inexhaustible creativeness. Aion is a winged figure with the head and claws of a lion, wound around by a snake and holding a key in each hand. A variation on this theme is the Orphic god Phanes, a winged youth surrounded by signs of the zodiac.

Gradually these images were superseded by the idea that the passage of time brings decay and decrepitude. Time began to be represented by the hourglass, the scythe and crutches; it came to be regarded as the bearer of misfortune, a force at once hostile and capricious. The 16th-century Florentine painter Bronzino entitled a painting "Venus, Cupid, Folly and Time" [*see illustration on page 124*]. Bronzino's French contemporary Georges Reverdy showed time and chance as antagonists: he represented inexorable time as preventing man from seizing chance.

Studies of the psychology of time bring up the subject of biological clocks. A familiar human example of such a mechanism is the capacity some people have to awaken at a preappointed time, often just a few moments before the alarm clock goes off. An example in animals is the ability to time entry into and emergence from hibernation. The first step toward a theory of biological clocks was made some 40 years ago by the French psychologist Henri Piéron. He suggested that if the rate of a subject's physiological processes were to be increased—by raising the body temperature, for example—the subject's private time would seem to pass more rapidly. Conversely, Piéron predicted, lowering the body temperature would make psychological time seem to pass more slowly. His pupil Marcel François



ESTIMATES OF THE PAST by different people show wide variation. Each subject was asked to mark off, on a 10-inch line rep-

put the hypothesis to a test in the laboratory by asking some subjects to tap a key at a rate of three times per second. He then induced an increase in their temperatures by diathermy and found that they tapped faster.

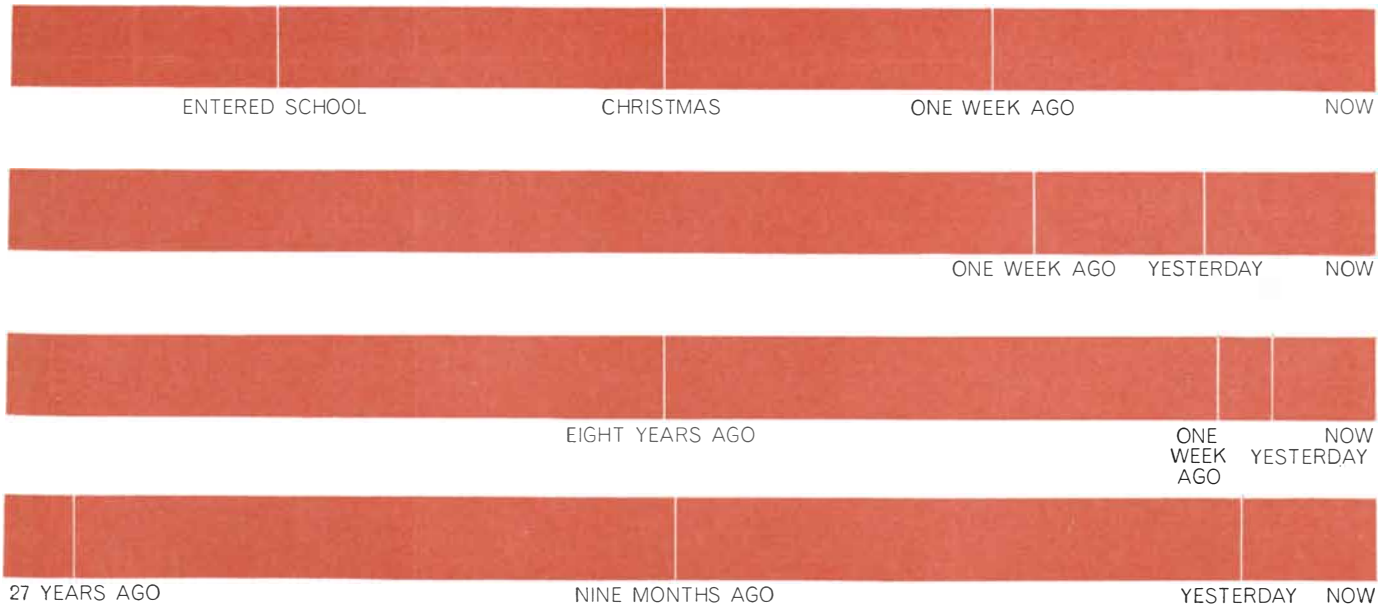
A more systematic treatment of the relation between temperature and inner clocks was undertaken by Hudson Hoagland of the Worcester Foundation for Experimental Biology. He has reported that he was launched on his inquiry by a domestic episode: his wife developed a temperature of 104 degrees Fahrenheit and asked him to go to a drugstore for some medicine. Although he was away for no more than 20 minutes, she insisted that he was absent much longer. Her insistence suggested to him that her sense of time had been affected by her high temperature. He checked his idea by a bedside counting test; it showed that subjective minutes seemed shorter to her at higher temperatures than at lower ones [*see illustration on next page*]. Hoagland thereafter explored the subject extensively and concluded that there are chemical pacemakers in the brain that govern the speed of its metabolism and thereby affect the rhythm of subjective time.

There is much other evidence that, whatever the extent of agreement between clock time and private time in ordinary circumstances, prominent indications of "inner clocks" appear in illness. A few years ago Curt P. Richter of the Johns Hopkins University School of Medicine reported that he had collected records of more than 500 patients "whose symptoms have varied with clocklike regularity." A notable case of this kind, involving a woman with Parkinson's disease, was reported in Germany some years ago. The patient was unable to speak coherently, walk or feed herself—except at 9:00 P.M. each day. As that hour approached her condition improved dramatically, and for three hours she was seemingly normal. The cycle persisted during an observation period of nine years.

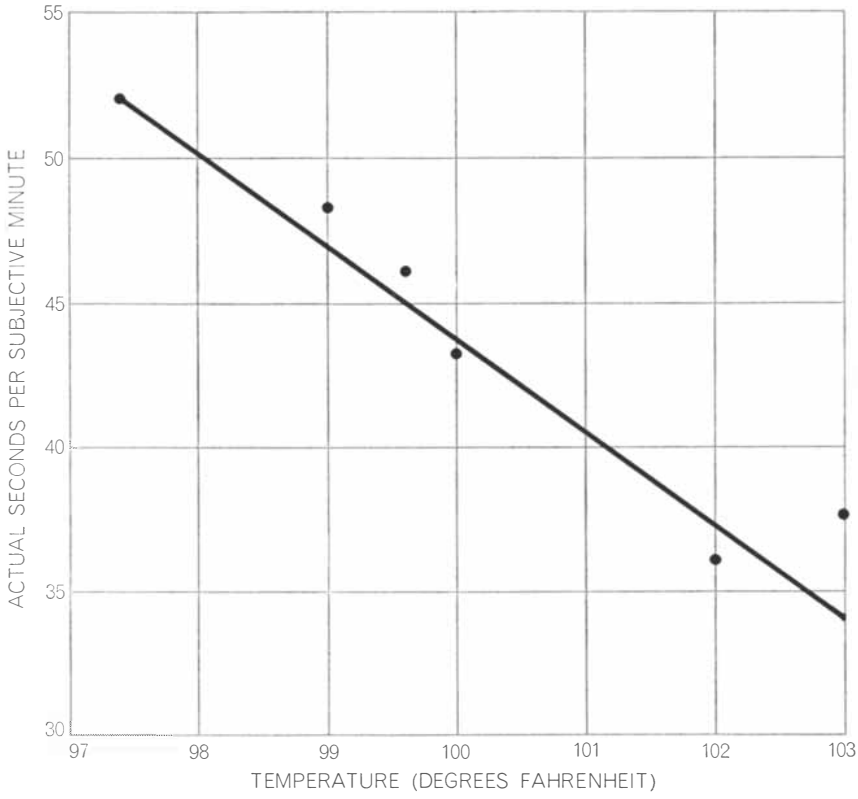
Similarly, a paretic, who suffers from progressive dementia and paralysis, may believe he has remained the same age since he first became infected with syphilis. Time for him has stood still. A victim of Korsakoff's syndrome, which is a chronic delirium usually arising from alcoholism, is likely to suffer impairment of the sense of the "pastness" of his experiences that is essential for normal recollection and the feeling of personal identity. Discrepancies between private time and clock time also appear in people who have taken drugs or are in heightened states of emotion. Under the influence of opium inner time is so accelerated that public time seems incredibly slow. Deformations of this kind suggest the variability and the limitations of biological clocks.

This biological basis of subjective time requires a new perspective for the studies of time to which psychologists and others have devoted themselves during the past century. Since human experiences last for a certain period and occur in succession, it is not surprising that the first question was: Does one's judgment of the duration and sequence of events differ from their duration and sequence as measured by clock or calendar? The experimental study of time was founded in 1860 with the attempt by the Austrian physicist Ernst Mach to examine this question in the sphere of auditory time. In an experiment designed by Mach the subject heard two successive series of beats from a metronome or an anvil and had to decide whether the duration of the second series was longer or shorter than the first or was of the same duration. Mach concluded that "the time of the physicist does not coincide with the system of time sensations."

Mach's technique was crude compared with the "time-sense apparatus" devised 30 years later by the German psychologist Ernst Meumann. With this apparatus Meumann could compare the apparent duration of two intervals of time; he could also examine, among other things, the relation between the apparent duration of intervals and the intensity of the sounds or lights delimiting the intervals. The apparatus consisted essentially of an arm mounted at the rim of a rotating wheel so that it would trip electrical contacts; the contacts could be set in various positions around the rim. The time intervals,



resenting his life from birth to "now," sections indicating how distant various days or events seemed. A logarithmic relation appeared for intervals within the past year or so: the more recent the event, the longer the relative length of line that subjects allotted to it. For longer intervals the relation was linear: the length of line marked off for five years was about five times that allotted to one.



TIME AND TEMPERATURE showed a correlation in a test made by Hudson Hoagland of the Worcester Foundation for Experimental Biology when his wife became ill and her sense of time seemed altered. The impromptu counting test showed that the higher her temperature was, the fewer actual seconds there were in what she regarded as a minute.

which were defined by the distance between contacts, were recorded on a drum, which could also be used to record the subject's responses. Both the instrument and the drum were driven by an electric motor [*see illustrations on opposite page*].

The work of Mach, Meumann and their many successors has provided some insight into three properties of man's inner clocks. The property that has been most intensively examined is the length of the brief interval of time that can be judged most accurately. The second property is related to the interval of time over which a series of stimuli may extend and yet be experienced as "unitary." The third property is the minimum perceptible duration between two excitations. I shall discuss these properties in turn.

In experiments seeking to establish the short interval that can be judged most accurately it is usual to ask the subject to compare one interval with another that is somewhat longer or shorter. It has become clear in these experiments that the slightest variation in procedure may affect the subject's temporal judgment, which is extremely sensitive to whatever else he is experiencing at the moment. Whether any pair of intervals compared are "empty" or "filled" seems to matter little as far as fineness of discrimination is concerned. All in all, the evidence seems to point to an interval in the range of .6 second to .8 second as the one most people can judge most accurately. Shorter intervals tend to be overestimated, longer ones underestimated. It must be acknowledged that some experimenters would dispute these conclusions.

Less open to doubt is the claim that the apparent duration of a brief interval is influenced by the intensity of the stimuli that delimit it. The more intense the stimuli are, the shorter the interval seems to be, at least when the stimuli are auditory. A reverse effect occurs, however, if the interval is defined by a continuous stimulus and the subject is asked to compare two equal intervals made up of stimuli of unequal intensity. The interval with the more intense sound seems to last longer than the interval with the less intense sound.

It is evident from many experiments that estimates of periods extending over a few seconds are more precise than those of periods occupying minutes or hours. Presumably this is because in a brief period the attention focuses on the interval itself, whereas in a longer period the mind wanders. Judgments then become more erratic because they are based on such indirect cues as the number and kind of activities that have occupied the time. In experiments at the University of Manchester my colleagues and I have found that the frequency of mind-wandering varies considerably from one individual to another. For example, some members of an audience listening to a 40-minute lecture of mine were subject to mind-wandering at least once every two minutes, whereas others seemed able to sustain unbroken attention throughout most of the period. We measured the frequency of mind-wandering by having each member of the class push a button connected with a recording apparatus in an adjoining room when he became aware that his thoughts had *returned* to the lecture. Distortion of temporal judgment can also be introduced by a total break in the "stream of consciousness," as everyone knows who has dozed off while traveling.

Experiments involving the second property of inner clocks—the interval of time in which a series of stimuli will be perceived as unitary—relate to the question of what a person regards as the present. The experiments could be classified as an attempt to define the "psychological present." One experimental technique has been to provide a continuous light or sound and ask the subject either to switch it off when his psychological present ceases or to indicate by a signal when the light or sound no longer seems to be present all at once—in other words, when he thinks of some part of the stimulus as past and more as coming.

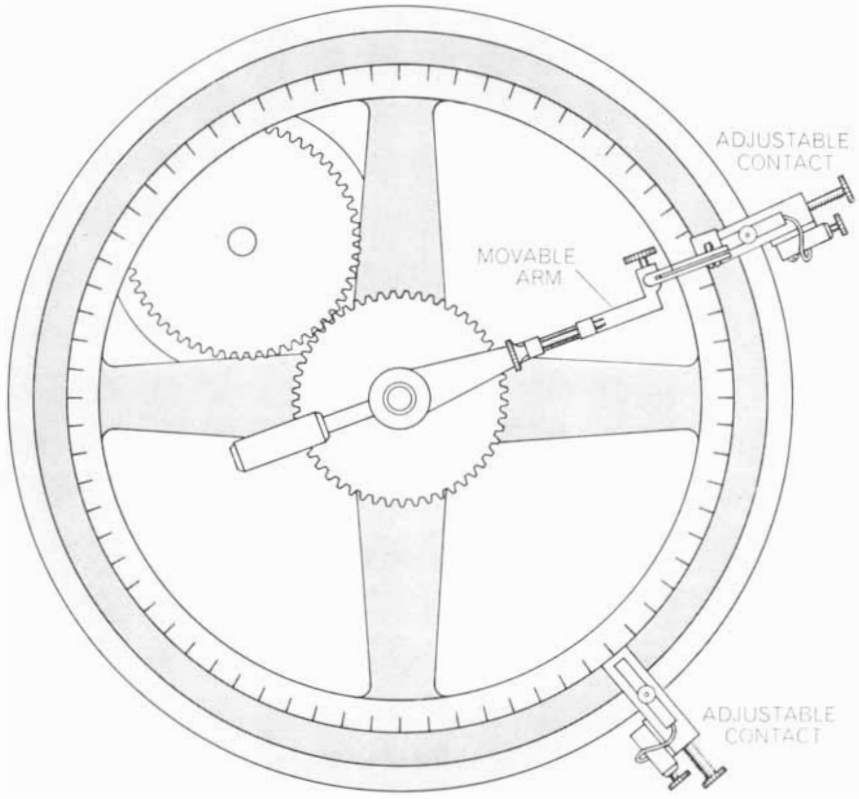
Efforts to establish upper limits for this interval encounter an intractable experimental difficulty in the ambiguity of the idea of a unitary experience; as a result upper limits ranging from two to 12 seconds have been indicated. With respect to lower limits the values reported range from .01 second for sound to .12 second for light. Here too there is a difficulty: it is in distinguishing what seems instantaneous from what seems to have some minimal duration, however transient. Such efforts face two unsolved problems. One is how to define an impression in terms of the critical rate (perhaps 18 per second) at which successive sensory elements are experienced as continuous. The other is how to define a moment in terms of the shortest interval in which information can be assimilated or integrated. A value of .1 second is suggested by

experiments that involve listening to a continuous list of words, because the listener loses very little information if the flow is electronically interrupted 10 times per second.

Two cautionary notes about such judgments are in order. One is that thresholds of the kind I have been discussing are not to be confused with thresholds of separation and order, which have been determined with some precision in auditory perception. An interval of two milliseconds (.002 second) separating two different sounds is enough to enable the listener to say he hears two sounds and not one; he needs an interval of about 20 milliseconds to report correctly the order in which the two sounds occur. My second caution is that one must beware of disregarding the relativity of human sensory powers with respect to any discriminatory experience. As Samuel Taylor Coleridge observed, "the delicious melodies of Purcell or Cimarosa might be disjointed stammerings to a hearer whose partition of time should be a thousand times subtler than ours, [just as] the edge of a razor would become a saw to a finer visual sense."

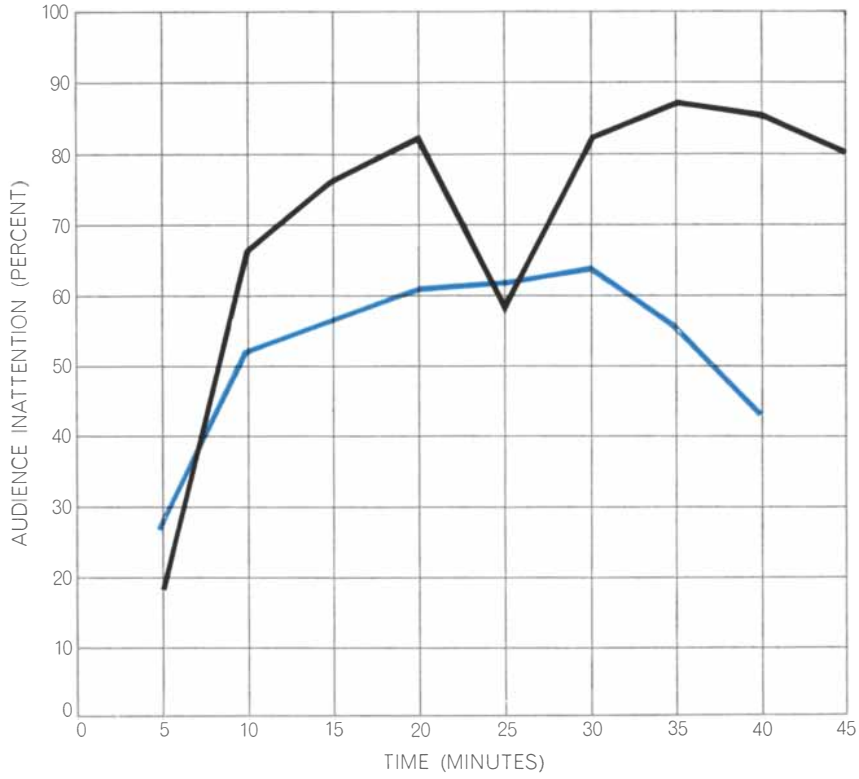
With these observations I turn briefly to the third property examined in the investigation of inner clocks: the minimum perceptible duration between two excitations. Experiments have shown that when both delimiting stimuli are auditory or tactile, the minimum perceptible duration is about 15 milliseconds. If both stimuli are visual, the minimum perceptible interval is about 75 milliseconds. Stimuli that involve two senses rather than one produce minimum perceptible intervals in the middle range: about 45 milliseconds for hearing and touch, 60 milliseconds for vision and touch and 90 milliseconds for vision and hearing.

What I have said so far points to an interrelation of inner clocks and sensory-motor activity. Each can influence the other. An instructive illustration is provided by an effect that Harry Helson of Kansas State University discovered and named the tau effect. It expresses a relation between time and estimates of distance. If three points are marked on the forearm of a subject and the interval of time between stimulating the second and third points is greater than that between the first and second, the subject believes that the distance between the second and third points is greater than that between the first and second, although in fact it may be the same or even less. In other



EARLY APPARATUS for testing subjective estimates of time was devised 70 years ago by the German psychologist Ernst Meumann. It consisted of an arm that met electrical contacts mounted on the rim of a wheel; distance between two contacts defined a time interval. Meumann had subjects compare two intervals or judge one under various delimiting stimuli.

MEUMANN'S MACHINE is more fully shown. Time intervals set by the movable contacts shown in the illustration at the top of this page were recorded on a drum, as were subjects' responses. Among other things, Meumann sought to learn how such stimuli as sounds and lights delimiting an interval affected a subject's judgment of the duration of the interval.



MIND-WANDERING affects time estimates by forcing reliance on indirect cues for judging intervals. Listeners were asked to signal when their thoughts returned to a lecture (*color*) or to recorded music (*black*). Curves show percentage of each audience signaling.

EFFECT OF DISTANCE on time estimates was shown in experiments in which subjects were asked to make the middle of three flashes that varied in spatial separation bisect the time interval between the first and third. They tended to allot the greater time to the shorter distance. The chart expresses this "kappa effect" as the extent to which the time between the second and third flashes differed from that between the first and second.

words, the subject's estimates of the distances are influenced by the time intervals that delimit them. A similar effect has been demonstrated in vision.

A converse effect, in which the subject's estimates of times are affected by distance, also occurs, as we and investigators in Japan have independently found. We have called it the kappa effect; I chose that name because kappa is the first letter of the Greek *"kurtos,"* meaning arched, and I had the impression of seeing an arch as I viewed the lights. Suppose the subject faces a horizontal or vertical row of three lights flashing in a cycle. The experimenter can vary the position of the middle light so as to obtain variations in the ratio of, on the one hand, the distance from the first light to the second and, on the other, the distance from the second light to the third. As he does so, the subject is asked to adjust the flashing of the middle light so that it bisects the interval of time between the flashes of the first and third lights. Our experience has been that under such conditions the subject will tend to allot the shorter time to the longer of the two distances. The magnitude of the kappa effect varies with the direction of the cycle of flashes: it is smallest in the upward direction, greatest in the downward and intermediate in the horizontal.

If the flashes of light are replaced by three tones of different pitch, an auditory kappa occurs. It is a weaker effect, however, possibly because the subject feels he can safely ignore pitch while adjusting the middle tone to bisect the time between the first and third. A kindred effect can be produced by indicating the whole time interval of the stimulus with a continuous tone that is alternated with another tone of a different pitch. The effect then becomes more marked: the subject allots a shorter duration to the higher tone than to the lower one. The greater the difference in the frequency of the two tones, the more striking the effect.

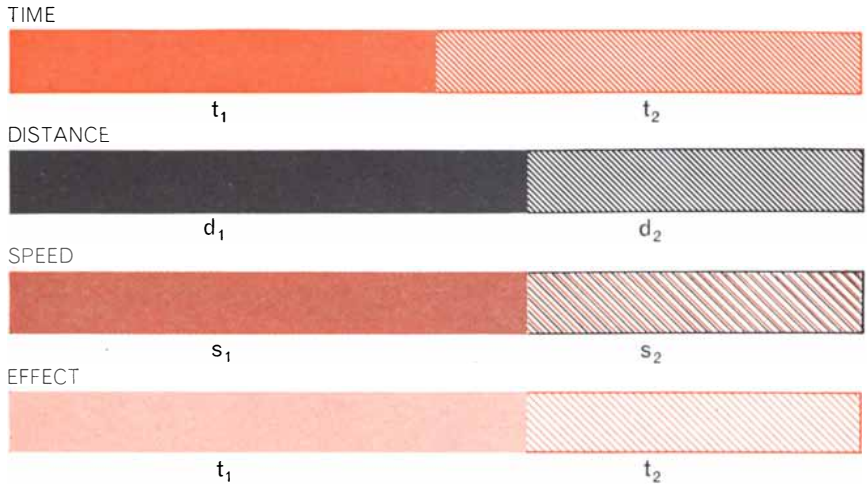
What would happen if distances were passively experienced, as when one is a passenger in an airplane? Would the distances then influence comparative judgments of two intervals of time? We have studied this problem in a situation where the subject is a passenger in an automobile and has to judge the duration of parts of a trip that vary in distance and speed. The same question can be studied in a variety of contexts involving the movement of a subject, either actively or passively, on land, in water, in the air or even in outer space. Suppose, for example, a man flew blind-

folded from London to Paris (210 miles) in an hour and then went on to Istanbul (1,400 miles) in another hour. Would the second lap of his journey seem longer than the first?

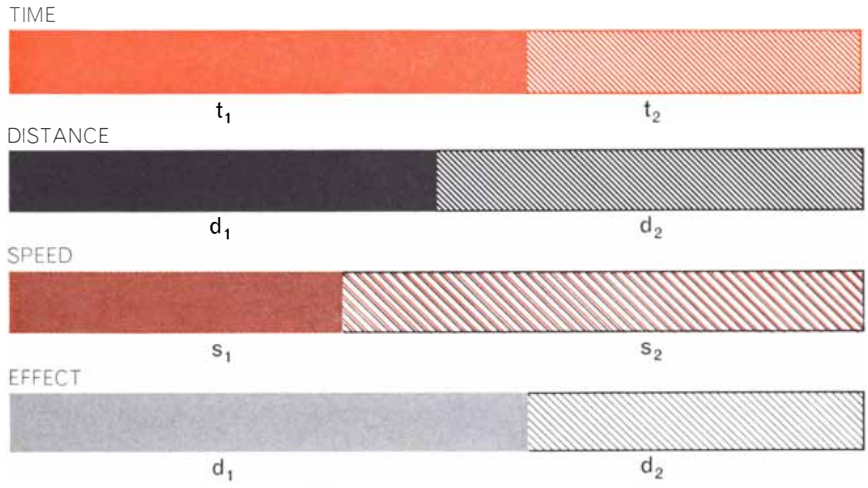
In order to exclude visual cues on our experimental road trip, we either blacked out the windows of the vehicle or blindfolded the subjects. They were then told that they were to be taken on a trip during which a bell would ring. When the trip was over, they estimated its duration, distance and speed before and after the sound of the bell. The chief outcome of these experiments is the demonstration of an interdependence of apparent duration, distance and speed such that if two parts of a trip take the same clock time, the part with the greater distance and speed seems to last longer. This we call the kappa-movement effect.

Two other effects also show up. First, the shorter distance is overestimated and the longer distance is, if anything, underestimated. From this, together with the tau effect, it is possible to infer that if two parts of a trip are of equal distance, the part traveled at a slower speed for a longer time will seem to have covered the greater distance. Second, the slower speed is overestimated and the faster speed is, if anything, underestimated. From this, again together with the tau effect, it is possible to infer that if two parts of a trip are traveled at the same speed, the part in which the distance and time are shorter will seem faster [*see illustrations at right*].

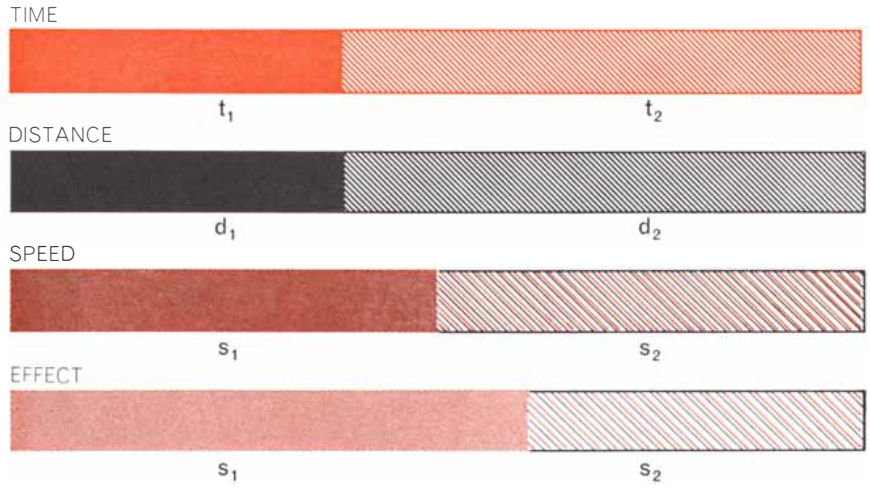
To what extent are the separate estimates of duration, distance and speed mutually consistent? Are they interrelated in a manner analogous to the interrelations of the physical variables: time, distance and speed? The answer is yes, provided that the passenger is traveling at a uniform speed. A change of speed, however, disturbs the symmetry of the relations. Passengers then believe they have been traveling for a longer time than is implied by their combined estimates of distance and speed. Furthermore, their estimate of speed is excessive as judged by the speed implied in their combined estimates of duration and distance, but they underestimate distance as judged by their combined estimates of duration and speed. It is worthy of note that the estimates of speed are most accurate when the vehicle travels at about 30 miles per hour. Below that speed passengers consistently tend to overestimate; above it they tend to underestimate. It is possible, of course, that their judgments are affected



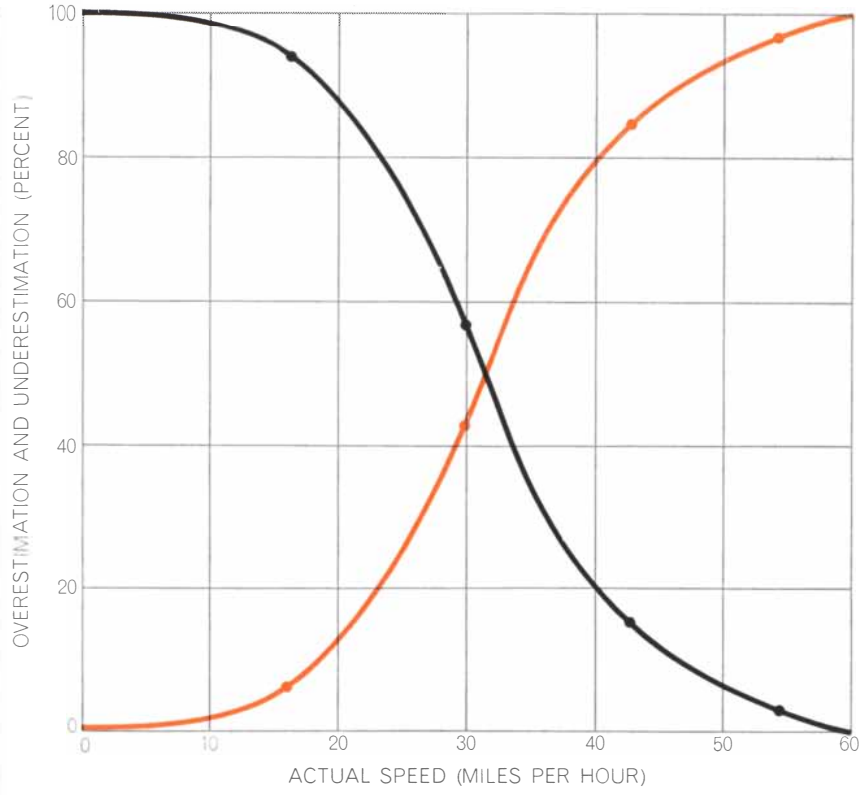
AUTOMOBILE TRIPS in which the first and second parts were separated by the sound of a bell produced a "kappa movement" effect. If the two parts took equal time but the first had the greater distance and speed, subjects thought the first part took the longer time.



SECOND VARIATION of the experiments involving automobile trips produced a "tau movement" effect. If the relations of the two parts of the trip were as shown in the chart, the subjects tended to think the first part had covered a greater distance than the second.



COMBINED EFFECT appeared when the first part of an automobile trip had the same speed as the second but covered a shorter distance and took less time than the second. Subjects then thought the first part of the trip had occurred at a higher speed than the second.



ESTIMATES OF SPEED by automobile passengers varied inversely with the actual speed. Colored curve shows underestimations; overestimations are represented by black curve.

by their knowledge of the speed limits.

One must not overlook individual differences, which have been brought into prominence by further experiments involving walking and running. A subject, accompanied by the experimenter, sets out walking; on a signal from the experimenter he begins to run. (The total distance is about 150 feet.) Some 50 percent of our subjects think the walked distance is the greater, although in fact the two distances are the same. In other words, the subjects show a tau-movement effect, and it is much stronger than in the case of the subjects who think the distance that was run was the greater. The former, whom we call the tortoise type, are more sensitive to the passage of time than the latter, whom we call the hare type. Those of the hare type focus on speed and so think they have covered a relatively longer distance when running for a shorter interval of time. Clearly comparative judgments of distance are influenced by the time intervals that delimit them, and the direction of the response reflects a time-sensitivity that is a function of variations in metabolism and individual tempo.

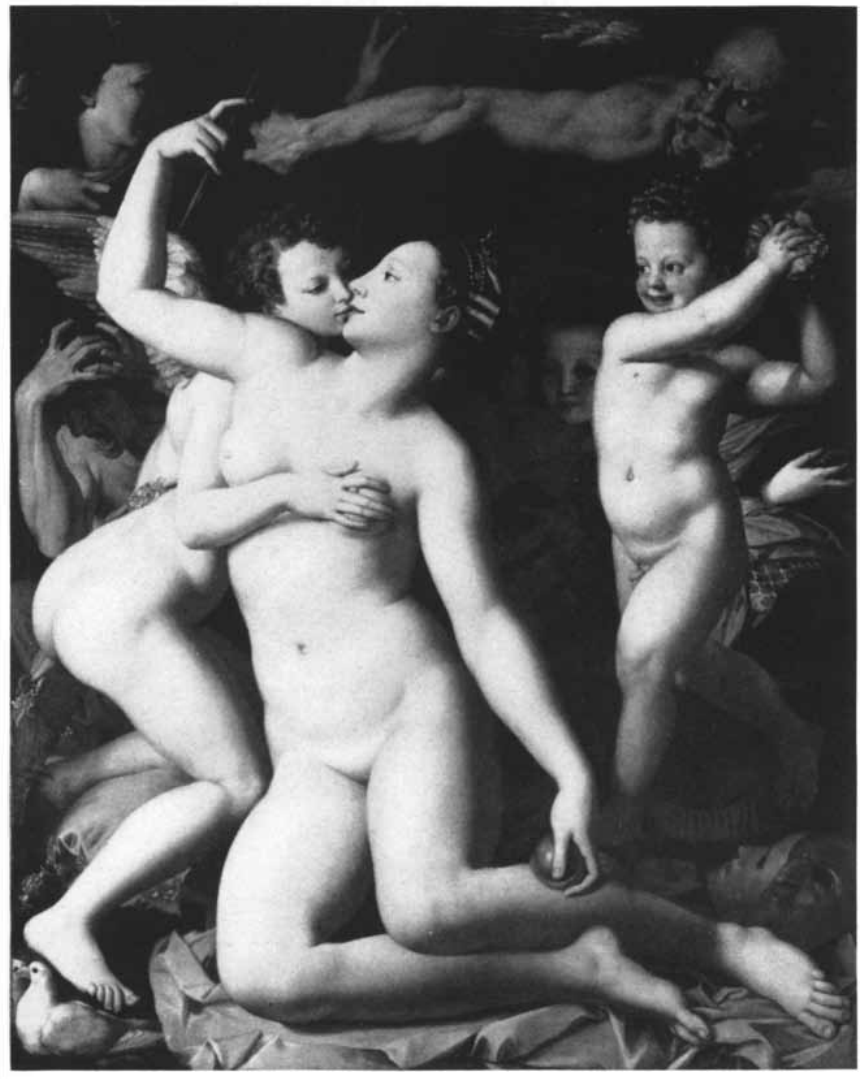
All these observations recall the questions posed by Albert Einstein to the psychologist Jean Piaget: "Is time immediate or derived? Is it integral with speed from the very outset?" Piaget, relying on his studies of how children develop ideas of time, has tentatively suggested that the notions of speed and distance are more basic, and that the idea of time is derived from them. Experiments along the lines of those I have described, although they are not decisive, may have a bearing on the problem; they may offer the possibility, by varying the conditions, of determining the order of kinship between the intuitive ideas of duration, speed and distance.

There is one more area of our experiments on duration that I wish to mention. These experiments seek to obtain a measure, crude though it may be, of the apparent duration of weeks, months or even years. We ask the subject to mark off, on a line of given length representing "birth" to "now," a section corresponding, say, to the time that has elapsed since yesterday's lunch, since last Christmas and so on. Such estimates of past time up to about six months before "now" show a relative contraction as they pertain to more and more remote events. Thus the length marked off for a day ago is disproportionately long compared with the length for a week or a month ago. Up to a point there appears to be a logarithmic rela-

tion between the length of line marked off and the interval it represents. That relation does not seem to hold for intervals greater than one year before "now," however; the length marked off for five years is approximately five times that marked off for one year.

Of all aspects of psychological time the most intriguing is the concept of the future. Everything human beings do presupposes a subjective future. They expect, intend, anticipate; they have premonitions and presentiments, even if these are not borne out by events. The entire psychic life of human beings is permeated with the thought of things to come; one's hopes for the future are the counterpart of one's nostalgia for the past. Even the simplest organism is surrounded by what Sir Charles Sherrington called "a shell of its immediate future." As the evolutionary scale is ascended the temporal horizon extends further and further ahead until in man it may reach beyond his own existence.

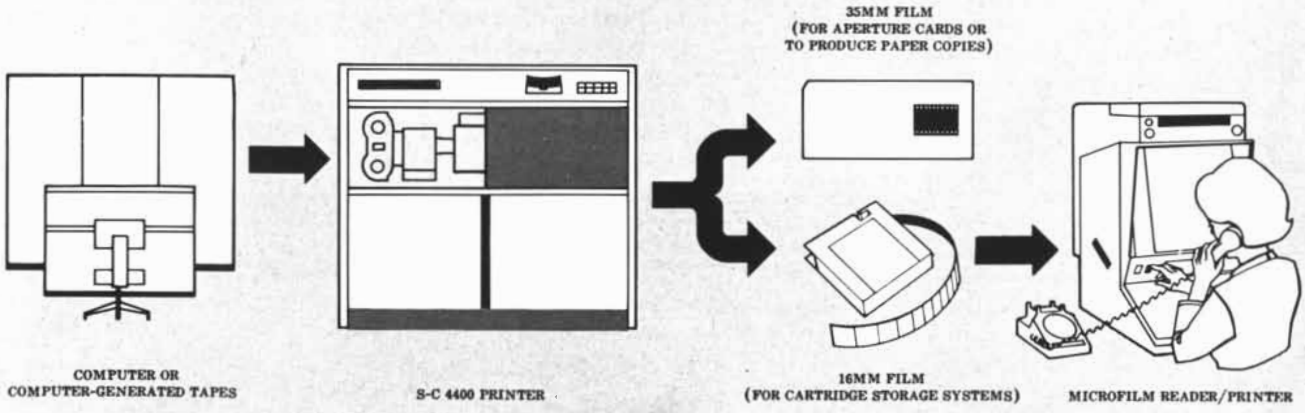
Two characteristics of thoughts about futureness are particularly noteworthy. First, one's orientation toward future events is often characterized by a "gradient of tension." The heart beats faster as the clock emphasizes that a fateful moment draws near. Every student who has to take an examination knows this feeling of mounting tension; so does the woman awaiting childbirth and the bridegroom awaiting the wedding ceremony. Second, there is a sense in which one's psychological future mirrors one's subjective past. In this sense, the further ahead one looks, the more the vision of a millennium resembles the golden age of the mythical past.



TIME AS REVEALER was depicted by Bronzino (Agnolo di Mariano), a 16th-century Florentine. Time (*top right*) pulls back a cloth to reveal Venus with Cupid and Folly. The painting, entitled "Venus, Cupid, Folly and Time," is in the National Gallery in London.

Announcing the S-C 4400 Printer

Speeds record retrieval, saves costly steps by instantly coding and recording computer output directly on microfilm



For the organization that handles large volumes of computer-generated records which must be available for fast retrieval, the new S-C 4400 can greatly increase the efficiency of the storage and retrieval system. The S-C 4400 records computer information on microfilm, which not only

occupies less storage space, but also lends itself readily to modern high speed retrieval of data. It is possible, for example, to locate one page out of a million and display it for viewing in only 15 seconds using these systems.

Eliminates Costly Steps: The S-C 4400 simplifies data processing by taking information from a computer and recording it directly on 16mm film for cartridge storage systems or 35mm film for aperture cards. The high speed recorder eliminates costly steps in the process of converting computer data into microfilm. 1. By operating on-line with the computer, there is no need to produce magnetic tape. However, the S-C 4400 can operate from computer-generated tape if desired. 2. The need for a paper printer is eliminated since selected pages can be produced on paper from the microfilm when required. 3. The tasks of manually handling paper and magnetic tapes are also eliminated. 4. In addition the job of microfilming and coding the output is accomplished automatically by the S-C 4400.

High Speed: Operating at printing speeds of 62,500 characters per second, the S-C 4400 electronically translates digital computer codes into ordinary language and records it on film at a rate of 50,000 pages per shift. Visual indexing codes compatible with most semi-automatic and automatic storage and retrieval systems are imprinted on the film automatically by the printer. A forms slide projector is available to superimpose the image of business forms over the film frames under computer program control.

Insurance companies, financial institutions, utilities, government agencies and other organizations which store large volumes of computer-generated data are able to retrieve information almost instantly when an S-C 4400 records the data directly on film. For further information on how you can lease the S-C 4400 for less than $4,000 a month write Stromberg-Carlson, Dept. E-54, P.O. Box 127, San Diego, California 92112.

STROMBERG-CARLSON
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MATHEMATICAL GAMES

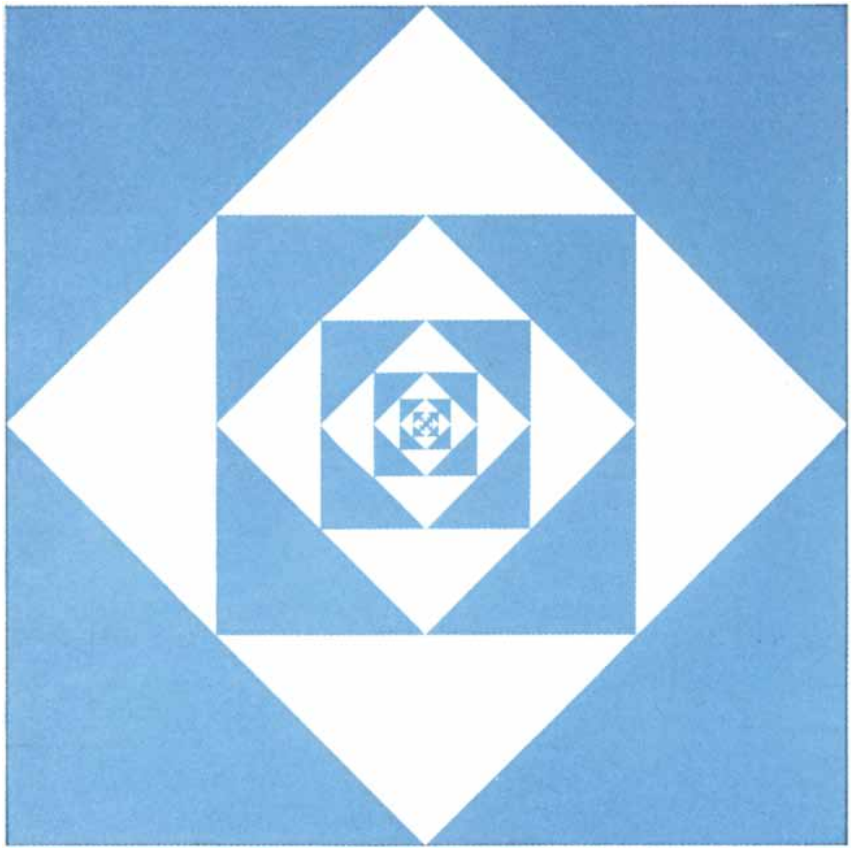
Some paradoxes and puzzles involving infinite series and the concept of limit

by Martin Gardner

For a mathematics student about to make the great leap from precalculus to calculus, no asset is more valuable than a firm, intuitive grasp of the concept of limit. The derivative and the definite integral, the fundamental tools of calculus, are both limits of infinite series. Every irrational number, such as pi, *e* and the square root of 2, is the limit of an infinite series. Perhaps an approach to the concept by way of recreation will help to dispel some of the difficulties that caused so much metaphysical confusion in the early history of calculus and that are still stumbling blocks in the path of a student today.

It was Zeno of Elea, a Greek philosopher of the fifth century B.C., who first demonstrated, with a famous series of paradoxes, how easily one falls into logical traps in talking about an infinite series. How, Zeno asked, can a runner ever get from *A* to *B*? First he must go half the distance. Then he must go half the remaining distance, which brings him to the 3/4 point. But before completing the last quarter he must again go halfway, to the 7/8 point. In other words, he goes a distance equal to the sum of the following series:

$$1/2 + 1/4 + 1/8 + 1/16 + \ldots$$



An infinite set of nested squares

The dots at the end mean that the series continues forever. How can a runner traverse an infinite series of lengths in a finite time? If you keep adding the terms of this series, you will never reach the goal of 1; you are always short by a distance equal to the last fraction added.

Now, there is a simple way to design an experiment so that in theory Zeno's contention is correct. Place a chess queen so that the center of its circular base rests on point *A*. The piece is to be pushed along a straight line to point *B* in the following way. First we push it a distance of 1/2, then pause until one second has elapsed. Then we push it a distance of 1/4 and again pause until the end of the second. We continue in this manner, beginning each push one second after the start of the previous push. At what time will the queen reach *B*? The answer is never. Suppose, however, we give the queen a constant velocity so that it covers half the distance in half a second, a quarter of the distance in a quarter of a second and so on. Both time and distance are now described by the same halving series. Both simultaneously converge—or "choke off," as mathematicians say—at the number 1. In one second, therefore, the queen reaches *B*.

What does a mathematician mean when he says that the "sum" of this halving series is 1? Clearly it is not a sum in the sense that one speaks of the sum of a finite series. There is no way to sum an infinite series in the usual sense of the word because there is no end to the terms that must be added. When a mathematician speaks of the sum—more precisely the limit—of an infinite series, he means a number that the value of the series approaches, as the number of its terms increases without bound. By "approach" he means that the difference between the value of the series and its limit can be made *as small as one pleases*. Here we touch the heart of the matter. The value of an infinite series sometimes reaches its limit and sometimes goes *beyond* the limit. A simple example of the latter is obtained by changing alternate signs in the halving series to minus signs: $1/2 - 1/4 + 1/8 - 1/16 + \ldots$. The partial sums of this series are alternately more or less than its limit of .3333... (which, incidentally, is a way of writing 1/3 as the limit of an infinite series of decimal fractions). The important point is that, in every case of an infinite series that chokes off, one can always find a partial sum that differs from the limit by an

amount smaller than any fraction one cares to name.

Finding the limit of a converging series is often extremely difficult, but when the terms decrease in a geometric progression, as in the case of the halving series, there is a simple dodge every reader should know. First let x equal the entire series. Because each term is twice as large as the next, multiply each side of the equation by 2:

$$2x = 2(1/2 + 1/4 + 1/8 + 1/16 + \ldots)$$
$$2x = 1 + 1/2 + 1/4 + 1/8 + \ldots$$

The new series, beyond 1, is the same as the original series x. So

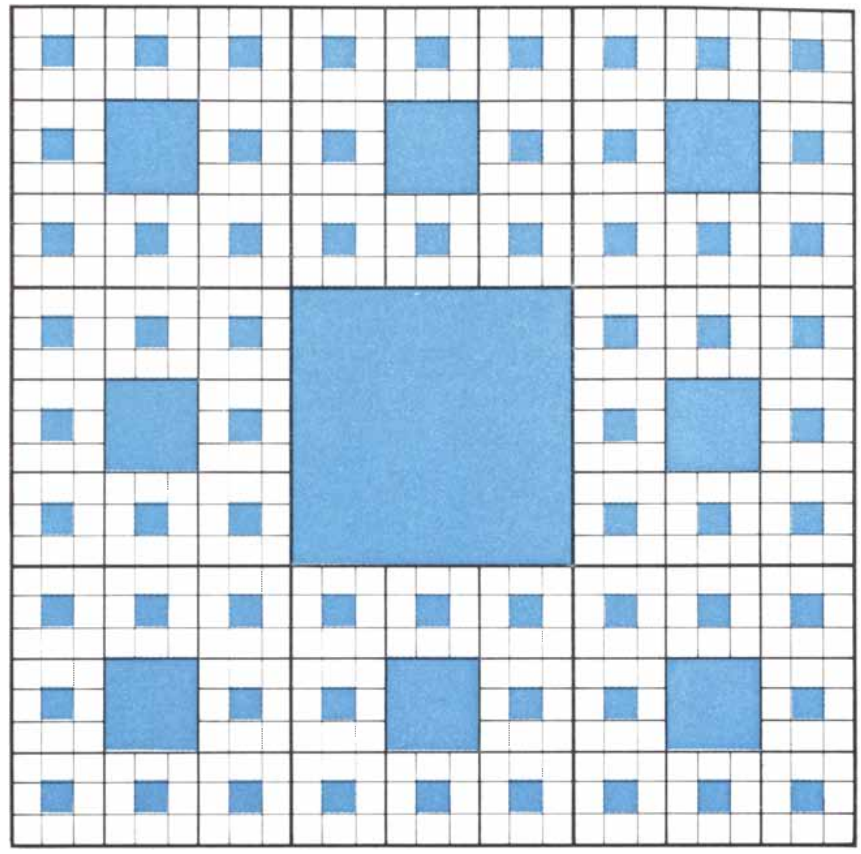
$$2x = 1 + x,$$

which reduces to $x = 1$.

Let us see how this applies to another of Zeno's paradoxes: the race of Achilles and the tortoise. Assume that Achilles runs 10 times faster than the tortoise, and that the animal has a lead of 100 yards. After Achilles has gone 100 yards the tortoise has moved 10. After Achilles has run 10 yards the tortoise has moved one. If Achilles takes the same length of time to run each segment of this series, he will never catch the tortoise, but if both move at uniform speed, he will. How far has Achilles gone by the time he overtakes the tortoise? The answer is the limit of the series $100 + 10 + 1 + .1 + .01 + .001 + \ldots$. Here we see at once that the sum is 111.111..., or 111⅑ yards. Suppose Achilles runs seven times faster than the tortoise, which has the same head start of 100 yards. How far must Achilles go to catch the tortoise?

(We leave aside the question of whether modern mathematics does or does not refute Zeno. It all depends, of course, on what one means in this context by "refute." The interested reader can find no better introduction to the difficult literature on this subject than Bertrand Russell's brief discussion in Lecture 6 of *Our Knowledge of the External World* and his more advanced analysis on pages 336–354 of *Principles of Mathematics*. Zeno's paradoxes raise questions about space, time and motion that are too deep to be answered frivolously, as they once were by Diogenes the Cynic: he stood up and walked from *A* to *B*.)

Bouncing-ball problems, found in many puzzle books, also yield readily to the trick just explained. Assume that an ideal ball is dropped from a height of one foot. It always bounces to 1/3 of its previous height. If each bounce takes a second, the ball will bounce forever, but since the time for each bounce also decreases by a converging series, the ball eventually stops bouncing even though it makes (in theory) an infinite number of bounces. The reader should have little difficulty determining how far this ideal ball travels before it comes to rest.



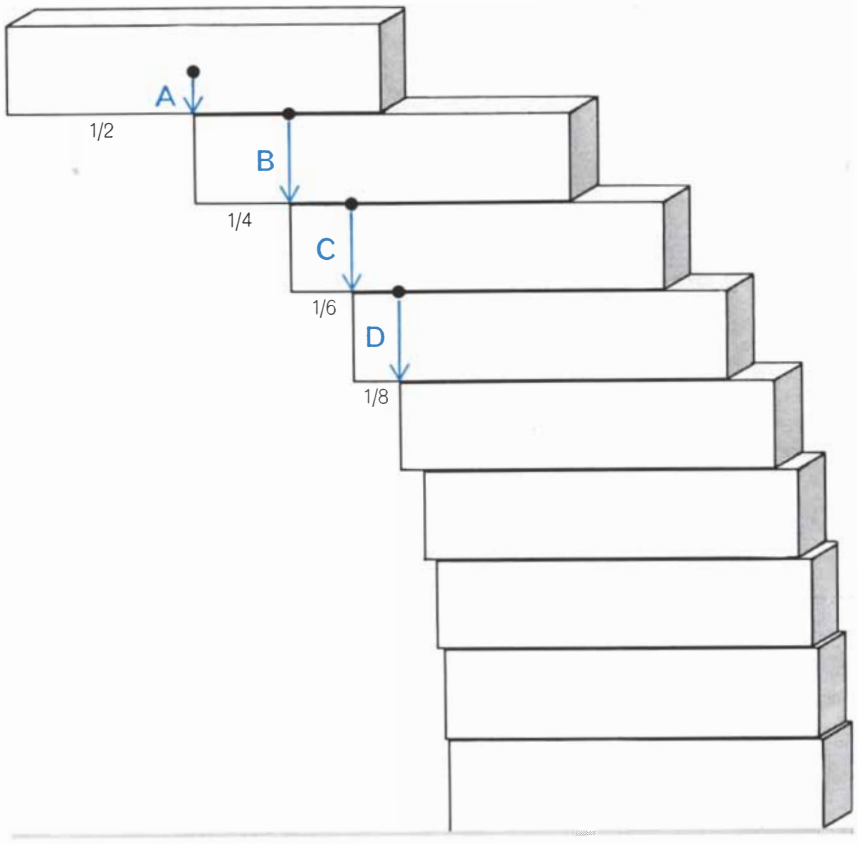
What is the limit of area for the colored portion?

Geometric examples of series of this type are legion. If the largest square in the illustration on the opposite page has a side of 1 and the nesting continues indefinitely, what is the area of the infinite set of squares? Obviously it is 1 plus the halving series previously considered, or a total area of 2. Only a trifle more difficult is the following problem, presented in 1905 in a competition held annually in Hungary. A unit square is divided into nine equal squares, like a ticktacktoe board, and the center square is painted a color. The remaining eight squares are similarly divided and painted. If repetitions of this procedure continue indefinitely [*see illustration above*], what is the limit of the painted area? This and the other questions will be answered in this department next month.

When a series does not converge, it is said to diverge. It is easy to see that $1 + 2 + 3 + 4 + 5 + \ldots$ does not choke off. Suppose, however, that each new term, in a series joined by plus signs, is *smaller* than the preceding one. Must such a series converge? It may be hard to believe at first, but the answer is no. Consider the series known as the harmonic series:

$$1 + 1/2 + 1/3 + 1/4 + 1/5 + \ldots$$

The terms get smaller and smaller; in fact, they approach zero as a limit. Nevertheless, the sum increases without bound! To prove this we have only to consider the terms in groups of two, four, eight and so on, beginning with 1/3. The first group, $1/3 + 1/4$, sums to more than 1/2 because 1/3 is greater than 1/4, and a pair of fourths sums to 1/2. Similarly, the second group, $1/5 + 1/6 + 1/7 + 1/8$, is more than 1/2 because each term except the last exceeds 1/8, and a quadruple of eighths sums to 1/2. In the same way the third group, of eight terms, exceeds 1/2 because every term except the last (1/16) is greater than 1/16, and 8/16 is 1/2. Each succeeding group can thus be shown to exceed 1/2, and since the



The infinite-offset paradox

number of such groups is unlimited the series must diverge. It does so, however, with infuriating slowness. The first 100 terms, for instance, total only a bit more than 5. To reach 100 requires more than 2^{199} terms. William Ransom of Tufts University once calculated that if each of these terms were printed on a half-inch square of paper (we ignore the fact that later fractions would have to be written in microscopic numerals to fit the squares), we could paper the entire surface of the earth with such squares, and not until we had added about 400 billion such layers would we exhaust the sheets!

The harmonic series is involved in an amusing problem that appeared in the *Pi Mu Epsilon Journal* for April, 1954, and more recently in *Puzzle-Math*, a book by George Gamow and Marvin Stern. If one brick is placed on another, the greatest offset is obtained by having the center of gravity of the top brick fall directly above the end of the lower brick, as shown by arrow *A* in the top illustration at the left. These two bricks, resting on a third, have maximum offset when their combined center of gravity is above the third brick's edge, as shown by arrow *B*. By continuing this procedure downward one obtains a column that curves in the manner shown. How large an offset can be obtained? Can it be the full length of a brick?

The unbelievable answer is that the offset can be as large as one wishes! The top brick projects half a brick's length. The second projects 1/4, the third 1/6 and so on down. With an unlimited supply of bricks the offset is the limit of

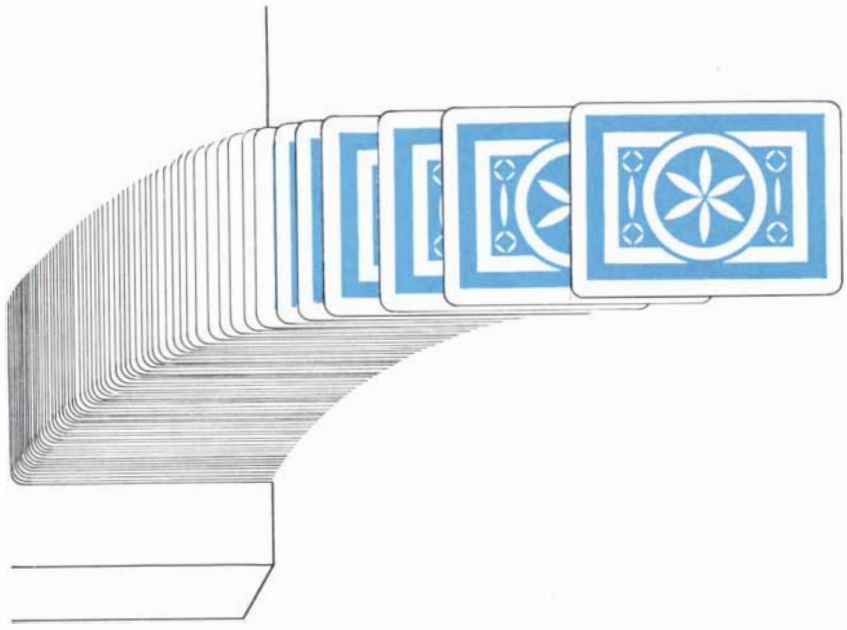
$$1/2 + 1/4 + 1/6 + 1/8 + \ldots$$

This is simply the harmonic series with each term cut in half. Since the sum of the harmonic series can be made larger than any number we care to name, so can half its sum. In short, the series diverges, and therefore the offset can be increased without limit. As we have seen, such a series diverges so slowly that it would take a great many bricks to achieve even a small offset. With 52 playing cards, the first placed so that its end is flush with a table edge, the maximum overhang is a little more than 2¼ card lengths [*see bottom illustration at left*]. Readers may enjoy seeing if they can build an offset, using one deck, that exceeds two card lengths.

The harmonic series has many curious properties. If every term containing the digit 9 is crossed out, the remaining terms form a convergent series. If the denominator of each term is raised to the same power n, and n is greater than 1, the series converges. If every other sign, starting with the first, is changed to minus, the resulting series

$$1 - 1/2 + 1/3 - 1/4 + 1/5 - \ldots$$

chokes off on the natural logarithm of 2, a number slightly smaller than .7. Does the value of the series ever reach (after 1, of course) a number that is an integer? If there were a simple formula for expressing the value of the series



The overhang of a deck of cards

Basic Research at Honeywell
Research Center
Hopkins, Minnesota

Beam Surface Interactions in Ultra High Vacuum Systems

In high vacuums the quantity of gases adsorbed on the surfaces in the vacuum is much greater than that contained in the volume. New studies of the interactions of beams with surfaces are making possible further understanding of the reactions that occur at the interface of a solid and a gas in a high vacuum environment.

Within an ultra high vacuum system, the reactions that take place at the surface may have an appreciable effect on the surrounding vacuum and on the properties of the solid itself. Continued progress in the fields of semiconductors, thin films, the vacuum phenomena related to space exploration and others have pressed the state of the art of vacuum physics. This field has long been of interest but many tools were lacking. The explosion in vacuum technology since the early 1950's, however, has resulted in considerable basic progress.

Recently lower pressures have been achieved and gauges and other instrumentation improved. We are now able to probe some fundamental questions:

1. What is the surface of a substrate like? What are the surface atom layers like? Is there an oxidized layer?
2. What is sitting down or adsorbed on the surface? With what energy is it bound to the surface?
3. Beams of photons, electrons, ions or atoms may strike the surface. When they do, what happens? What are the interactions?

If we could answer all these questions we could develop a model with specific constants.

Honeywell scientists have chosen a research technique whereby particle beams are used to probe a surface in an ultra high vacuum environment. Components leaving the surface (that is, neutral atoms, neutral molecules and positive or negative ions) are analyzed with a mass spectrometer.

A series of studies is being made to see what effect varying parameters have on the components leaving the surface. The kind of beam used, the kind of substrate and the temperature of the substrate as well as the content of the vacuum environment are varied.

Honeywell scientists use an evacuated system pumped by cryogenic and ion means resulting in a background pressure of about 10^{-10} Torr.

A target with surface temperatures controlled by heaters is mounted in an interaction chamber and bombarded. All particles leaving the target pass through a mass spectrometer analyzer. Probing is done with very low density beams since the detection system permits recording of single ions or partial pressures as low as 10^{-16} Torr.

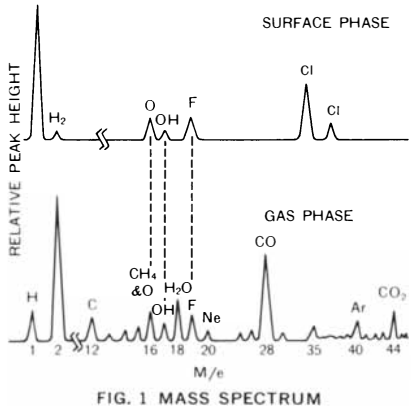


FIG. 1 MASS SPECTRUM

Lower Plot—gas phase components in the system at a total pressure of about 1x10-9 Torr.

Upper Plot—spectrum of surface phase obtained by bombarding single crystal nickel with electrons and analyzing the desorbed ion components.

These experiments have produced several unexpected observations:

1. Electron bombardment will desorb neutral molecules, suggesting an interaction between the electron and the adsorbed molecule.
2. Ions are desorbed at the same time and appear to be fragments of the parent adsorbed molecule, suggesting ion fragment desorption.
3. No parent molecule ion desorption was observed.

These studies indicate the existence of a whole spectrum of electron-induced ion desorbed species, permitting the analysis of surface phase components in a manner similar to that used for gas phase components. The technique also permits continuous observation of surface components as parameters are varied.

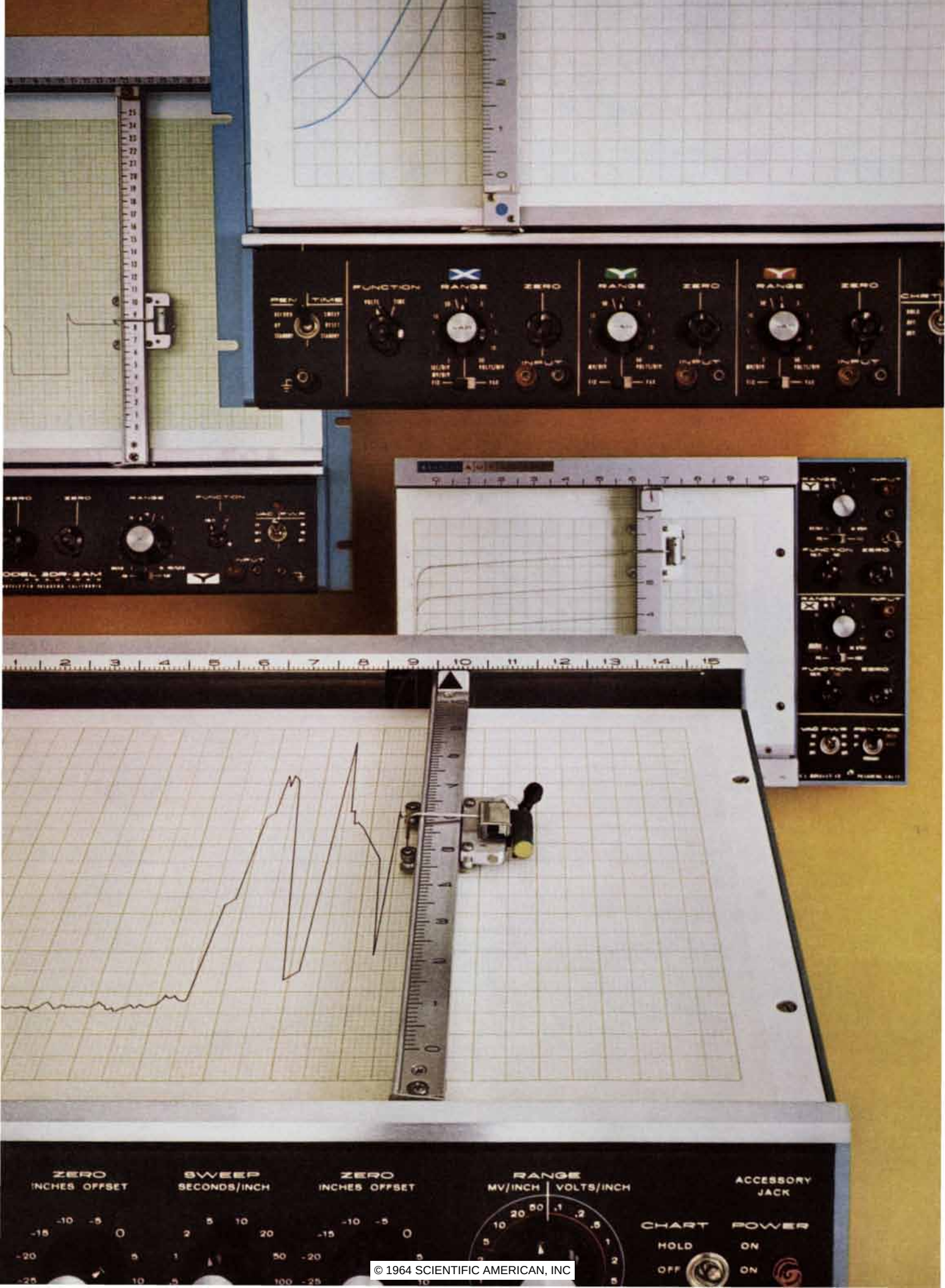
Bombardment with U.V. photons has also desorbed neutral molecules. This suggests that photon interaction might be used to clean surfaces in a vacuum without any heating effects.

Work is continuing at Honeywell's Research Center and as more parameters are introduced even more understanding seems possible. As an example, a ruby laser was used to bombard the target causing thermal desorption and permanent degassing of an extremely small area of the target. This technique will permit further exploration and comparisons of the degassed spot and surrounding surfaces.

Although a long way from a final theory, the new techniques already have provided information of value in programs as diverse as electrical contacts, U.V. detectors and space instrumentation.

If you are engaged in vacuum surface physics and wish to know more about Honeywell's work in this area you are invited to write Mr. David Lichtman, Honeywell Research Center, Hopkins, Minnesota. If you are interested in a career at Honeywell's Research Center and hold an advanced degree, write Dr. John Dempsey, Director of Research at this same address.

Honeywell



Francis L. Moseley built the first x-y recorder in 1935 to plot vacuum tube characteristics automatically. In 1951 he formed a company to build the first commercially available x-y recorder.

Science at last could produce significant, permanent recordings of two independent variables without laborious manual plotting. Today, F. L. Moseley Co. (since 1958 affiliated with Hewlett-Packard) remains the leading and, in many cases, the only source of state-of-the-art x-y recording capabilities.

Recorder precision was pioneered by establishing basic recorder accuracy of 0.2% of full scale with basic sensitivity of 5 millivolts full scale. The zener diode internal reference used by Moseley brought new absolute accuracy to recording mechanisms by comparing the input with a recorder-controlling voltage more precise than any previously known.

The newest Moseley recorders feature a five-to-one improvement in recorder sensitivity, common mode rejection to 140 db, and high impedance input circuits. They provide one inch of pen movement for as little as 100 microvolts signal input; they accurately plot small variations in high level voltages; and they make measurements without interfering with the circuits being measured.

The reliability and versatility of Moseley recorders have become standards of the industry. Other achievements include high-accuracy time sweep for recording one variable against time, with adjustable sweep length and automatic reset; electric paper holddown to replace noisy, less efficient vacuum systems; solid-state reliability; a variety of x-y recorders from 8½"x 11" to 32" x 32"; two-pen models, automatic chart advance, and today's most complete line of x-y recorder accessories.

For applications ranging from simple production line testing to the most sophisticated of scientific research, the x-y recorder is a convenient tool for producing an easily read plot of any phenomena that can be converted into electrical signals. By providing a complete range of such recorders, economy models to today's most advanced, Hewlett-Packard makes another important contribution to the science of electronic measurement and display.

for the RECORD

you can do your best plotting with Moseley recorders from Hewlett-Packard

Hewlett-Packard's Moseley affiliate offers 52 models of x-y recorders, one ideal for your recording need. They range in price from $975 for a minimum-requirement type to $3950 for the largest plotting boards. In addition, the company delivers a line of flexible strip chart recorders, plus today's most complete line of complementary accessories. Contact your local Hewlett-Packard field engineer for complete data or a demonstration of any model.

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Curves on recorders (top to bottom) show: comparative diode characteristics; distorted square wave plotted from sampling oscilloscope; transistor characteristics; nuclear pulse height analyzer plot.

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for n terms, this might be easily answered, but there is no such formula. An ingenious odd-even argument, however, that goes back at least to 1915 (the details are given on page 48 of the *American Mathematical Monthly* for January, 1934) shows that the series never reaches an integral sum.

If all the terms of an infinite series are positive, it clearly does not matter how the terms are grouped or rearranged; the limit remains the same. But if there are negative terms, it sometimes makes a big difference. From the 17th century to the middle of the 19th, before laws of limits were carefully formulated, all sorts of disturbing paradoxes were produced by juggling the plus and minus terms of various infinite series. Luigi Guido Grandi, a mathematician at the University of Pisa, considered the simple oscillating series $1 - 1 + 1 - 1 + 1 - \ldots$. If one groups the terms $(1 - 1) + (1 - 1) + (1 - 1) + \ldots$, the limit is 0. If one groups them $1 - (1 - 1) - (1 - 1) - \ldots$, changing the signs within parentheses as required, the sum is 1. This shows, Grandi said, how God could take a universe with parts that added up to nothing and then, by suitable rearranging, create something.

The correct limit for the original series, Grandi declared, is 1/2. He supported this by a parable. A father wills a precious stone to two sons with the proviso that every year the stone go from one to the other. If the value of the stone is 1, then its value to each son is the sum of $1 - 1 + 1 - 1 + \ldots$. Since the two brothers share the legacy equally, this value must be 1/2. Many distinguished mathematicians joined in the controversy over this series. Both Gottfried Wilhelm von Leibniz and Leonhard Euler agreed on the 1/2, although for somewhat different reasons. Today the series is recognized as divergent, so that no meaningful limit can be assigned to it.

An even worse instance is provided by the series $1 - 2 + 4 - 8 + 16 - \ldots$. Group it $1 + (-2 + 4) + (-8 + 16) + \ldots$ and you obtain the series $1 + 2 + 8 + 16 + \ldots$, which diverges to positive infinity. Group it $(1 - 2) + (4 - 8) + (16 - 32) + \ldots$ and you get the series $-1 - 4 - 16 - 64 - \ldots$, which diverges to infinity in the negative direction! The climax to all this infernal hubbub came in 1854 when Georg Friedrich Bernhard Riemann, the German mathematician now well known for his non-Euclidean geometry, proved a truly remarkable theorem. Whenever the limit of an infinite series can be changed by regrouping or rearranging the order of its terms, it is called *conditionally* convergent in contrast to an *absolutely* convergent series, which is unaffected by such scrambling. Conditionally convergent series always have negative terms, and they always diverge when all their terms have been made positive. Riemann showed that any conditionally convergent series (such as the one previously cited that chokes off on the natural logarithm of 2) can be suitably rearranged to give a limit that is any desired number whatever, rational or irrational, or even made to diverge to infinity in either direction.

Even an infinite series without negative terms, if it diverges, can cause serious trouble if one tries to handle it with rules that apply only to finite and converging series. For example, let x be the infinite, positive sum of $1 + 2 + 4 + 8 + 16 + \ldots$. Then $2x$ must equal $2 + 4 + 8 + 16 + \ldots$. This new series is merely the old series minus 1. Therefore $2x = x - 1$, which reduces to $x = -1$. Thus we seem to have proved that -1 is infinite and positive. One can sympathize with the Norwegian mathematician Niels Henrik Abel, who wrote in 1828: "The divergent series are the invention of the devil, and it is a shame to base on them any demonstration whatever."

Readers of this department were asked last month to supply President James Garfield's proof of the Pythagorean theorem. Referring to last month's diagram, the area of the entire figure—trapezoid *ABED*—is the product of its base, $x + y$, and half the sum of its sides, x and y. This can be written

$$\frac{(x + y)(x + y)}{2}.$$

The area of the trapezoid is also the sum of the areas of the three triangles. The largest triangle has an area of $z^2/2$, and each of the other two (congruent) triangles has an area of $xy/2$. We express the trapezoid's area as

$$\frac{z^2}{2} + \frac{2(xy)}{2}.$$

The two expressions for area are equal, so we have the equation

$$\frac{(x + y)(x + y)}{2} = \frac{z^2}{2} + \frac{2(xy)}{2},$$

which simplifies to $x^2 + y^2 = z^2$.

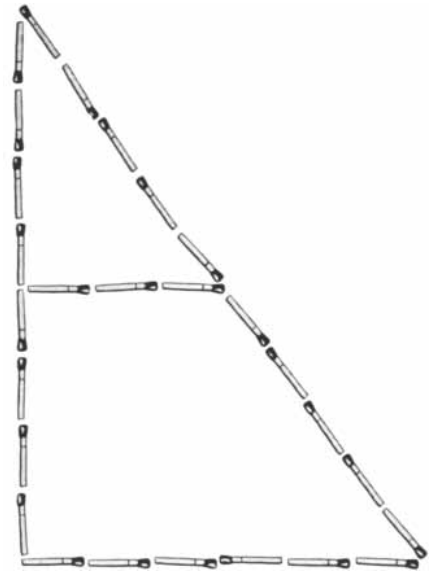
The four problems involving Pythagorean triangles are answered as follows:

1. Triangles 5, 5, 6 and 5, 5, 8 have equal areas because each can be split in half to make two 3, 4, 5 triangles.

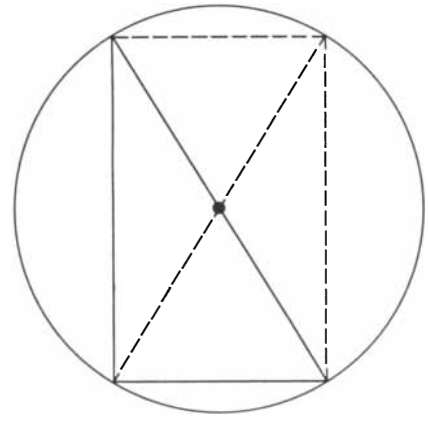
2. The smallest Pythagorean triangles with the same perimeter are 30, 40, 50; 24, 45, 51, and 20, 48, 52. Each has a perimeter of 120. The three smallest primitive Pythagorean triangles with equal perimeters are 3,255, 5,032, 5,993; 7,055, 168, 7,057, and 119, 7,080, 7,081.

3. Two noncongruent Pythagorean triangles—3, 4, 5 and 6, 8, 10—can be formed simultaneously on the plane with as few as 27 matches [*see upper illustration below*].

4. The diameter of a circle circumscribed about any right triangle is equal to the triangle's hypotenuse, as is evident from the lower illustration below.



Answer to the match problem



Circumscribing a right triangle

THE AMATEUR SCIENTIST

Moiré patterns provide both recreation and some analogues for solving problems

Conducted by C. L. Stong

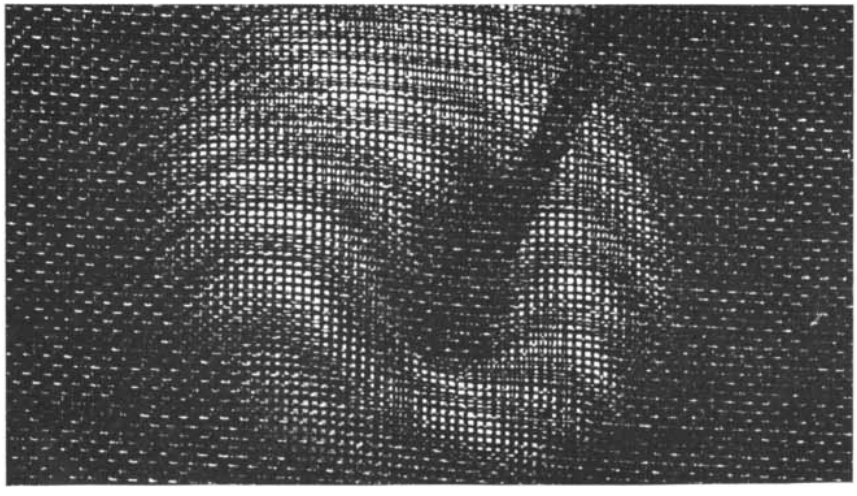
Every amateur should spend some time discovering the delights of moiré patterns, the geometric designs that appear when two or more repetitive figures of about the same spacing overlap at a small angle [see "Moiré Patterns," by Gerald Oster and Yasunori Nishijima; SCIENTIFIC AMERICAN, May, 1963]. Like crystals, the patterns are found throughout nature; moreover, they make playthings just as fascinating as crystals. Moiré patterns may turn up wherever repetitive phenomena exist. For this reason they can disclose relations in structures and events that otherwise appear to be widely diverse. As a consequence the moiré technique has found application in many departments of science as well as in some of the arts, including painting and music.

Essentially the relations disclosed by moiré patterns are mathematical. A moiré pattern is the graphic solution of an equation. Problems to be solved by the moiré technique must of course be stated in terms of repetitive figures, but they may range in complexity from simple arithmetic to the calculus of vectors. One class of problems that lends itself readily to solution by the moiré technique involves the determination of surface contours. Amateur telescope makers use it frequently for determining when a glass mirror has been polished to the figure of a paraboloid. During the polishing operation the mirror is examined from time to time through a grid of closely spaced lines known as a Ronchi ruling. The rulings interact with their own distorted shadows to generate a moiré pattern. Polishing is stopped when the mirror maker observes the desired result: the pattern generated by the intersection of a grid with its image as reflected by the mirror when it has become paraboloidal.

A similar experiment can be performed with a teaspoon and a piece of window screening. When the bowl of the spoon is viewed through a flat piece of screening in contact with the convex surface of the bowl, a moiré pattern appears as a set of distorted ellipses that depict the contour. A more striking effect can be created by substituting a rubber balloon for the spoon. When the shape of the balloon is altered, even minutely, the moiré pattern presents an exaggerated picture of the change. Gerald Oster of the Polytechnic Institute of Brooklyn, coauthor of the article mentioned above, has suggested this phenomenon as a stratagem for making a contour map of the moon. He would project a grid of known dimensions on the lunar surface and photograph it. The resulting pattern would disclose surface features that escape not only telescopes but also cameras in close lunar orbit. (When I asked Oster what kind of projector he had in mind, he replied: "Having made the proposal, I leave the details to specialists.")

Other moiré patterns can be generated by materials commonly found in the home: two superposed pieces of nylon stocking, for example, or superposed tracings of the grooves in a phonograph record. The most interesting experiments, however, require accurately drawn figures of known dimension. A set of figures of this type has recently been introduced by the Edmund Scientific Co. of Barrington, N.J. This kit includes eight repetitive figures, each presented twice: once on transparent plastic and again on photographic paper. The kit comes with a manual by Oster entitled *The Science of Moiré Patterns*. One produces moiré patterns by laying a transparency over its opaque counterpart; constant moving of the transparency will produce constantly changing patterns. The eight figures are as follows: a coarse grid of 13 lines per inch; a fine grid of 65 lines per inch; a grid with logarithmic spacing; 144 equally spaced radial lines; concentric circles with a spacing of 65 lines per inch; a "Fresnel zone" plate; a projection of a sphere, and projections of a cylinder [*see illustrations on opposite page*].

The moiré patterns that can be generated by this kit are explained most clearly, according to Oster, in terms of projective geometry. Each of the figures can be regarded as the silhouette



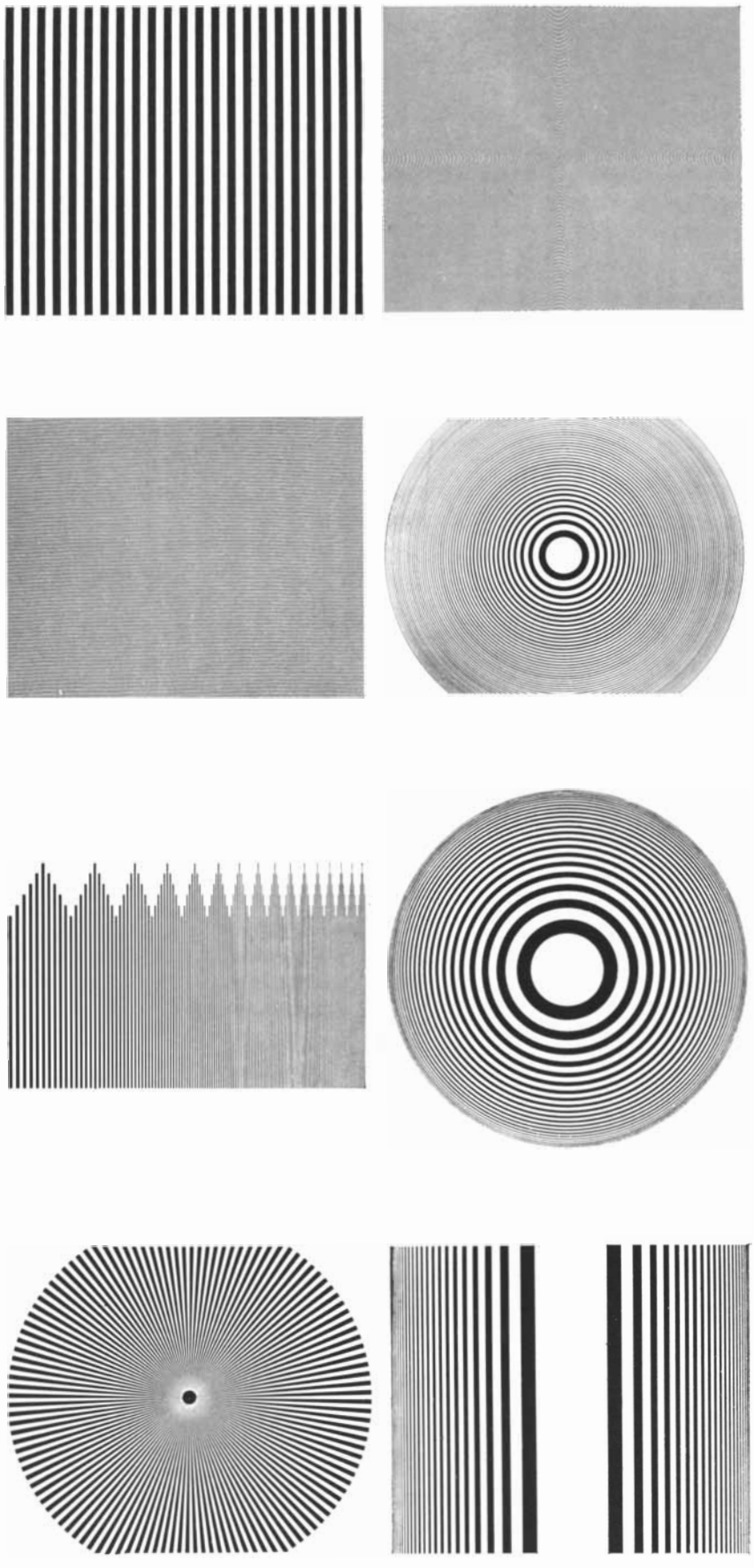
Window screening over a distorted balloon

of a three-dimensional object made of wire. A cone, for example, can be built up by spacing wire circles of decreasing diameter above one another. When the structure is lighted from the top by a point source of light, shadows of the wires appear as a set of concentric circles. Similarly, an inclined ladder of wires casts a shadow in the form of a grid. The spacing between the shadows of the cross wires varies with the angle at which the structure is inclined: it is at a maximum when the ladder is in contact with its shadow and at a minimum when the ladder makes a right angle in relation to the plane of the shadows. When the wire ladder (which represents a plane) is inclined at some angle above the wire cone, the overlapped shadows generate a moiré pattern in the form of either a circle, an ellipse, a parabola or a hyperbola—the form depending on the inclination of the wire grid with respect to the plane of the shadows [*see top illustration on page 137*].

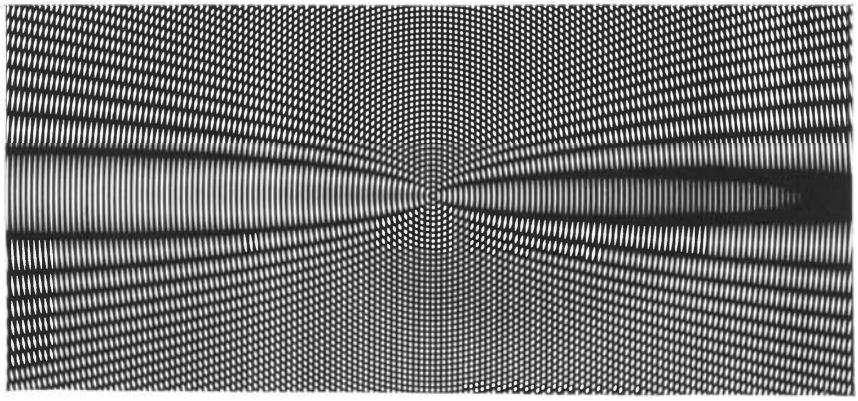
From the point of view of projective geometry, then, a set of concentric circles is equivalent to a cone; a grid, to a plane. When any figure made up of concentric circles is superposed on a grid of about the same spacing, the combination generates a moiré pattern that belongs to the class of curves known as the conic sections. If the spacing between the lines of the overlapping grid equals that between the concentric circles, say 65 lines per inch, the resulting moiré is a parabola, the curve generated when the intersection parallels the side of the cone.

In the case of a wire model the spacings of the grid can be altered by changing either the inclination of the ladder or its distance from the light. Moving the ladder closer to the light causes the shadows of the grid to spread apart, just as though it were inclined at a smaller angle. At this "inclination" the pattern becomes an ellipse, as can be demonstrated by lifting the transparent grid of the Edmund set while viewing the concentric circles. Two sets of ellipses will be seen because the grid represents either or both of two planes, one inclined to the left and the other to the right. Interchanging the figures—viewing the grid through the circles—decreases the spacing of the grid in relation to that of the circles (increases the angle of intersection). The figures now generate sets of hyperbolas.

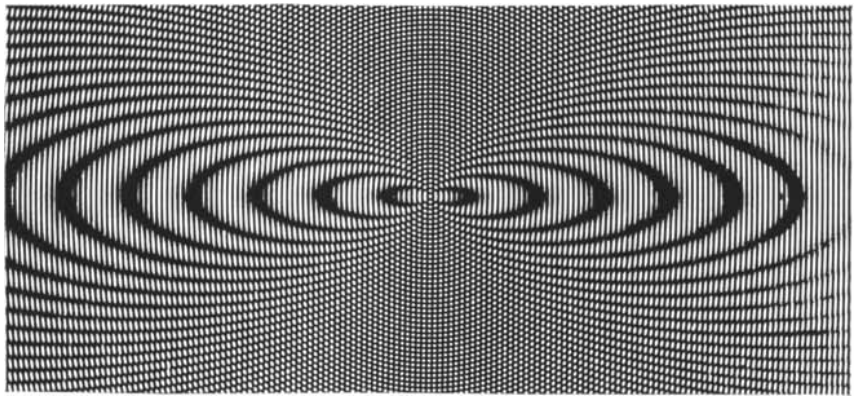
The logarithmic grid, as interpreted by projective geometry, is a curved surface: the shadow pattern that would be cast by a ladder bent into a logarithmic



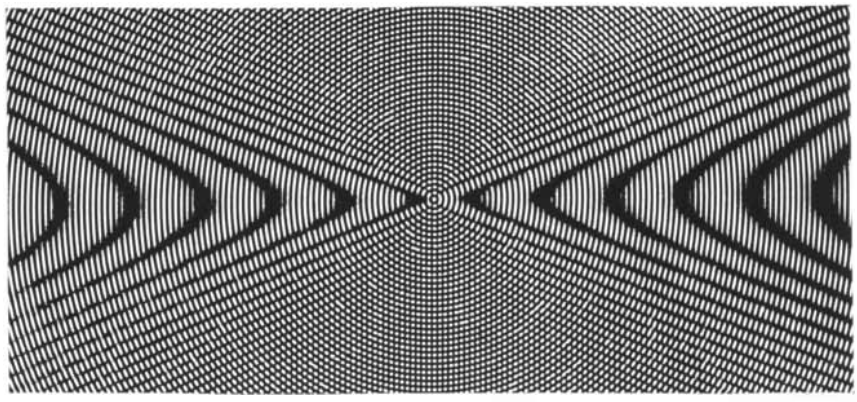
Set of repetitive figures for generating moiré patterns



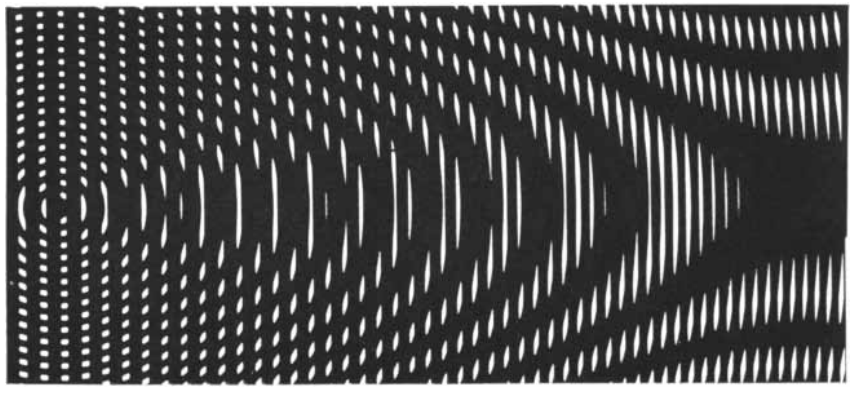
A conic-section pattern: the parabola



Another conic-section pattern: the ellipse



A third of the conic sections: the hyperbola



The entire family of conic sections

curve. Cross wires in the steepest part of the curve cast narrowly spaced shadows. The spacing increases smoothly as the curve flattens. Superposing the concentric circles on the logarithmic grid is equivalent to cutting a cone with a curved knife: the "intersection" generates the whole family of conic sections. Again, the experimenter must expect some ambiguity; a set of concentric circles can be interpreted as the projections of abutting cones. Similarly, the "curve" of the logarithmic grid can be interpreted as bending upward or downward [*see illustrations at left*].

By the same reasoning a pattern of radial lines can be interpreted as a helix seen by viewing a circular staircase from the top or bottom. The radial lines give no clue, however, to the direction in which the helix rotates. For this reason a pattern of radial lines superposed on a repetitive structure of any kind displays two sets of moiré patterns, and, if it is used as an analogue computer, it generates two solutions. The solution of interest must be distinguished by taking the conditions of the problem into account.

The Fresnel-zone plate is the projection of a paraboloid. The intersection of a pair of closely spaced paraboloids that point in the same direction generates a plane. When a pair of Fresnel-zone plates are overlapped at a short center-to-center distance, the resulting moiré pattern consists of straight lines that represent one edge of the planes of intersection. When one parabola (Fresnel-zone plate) of the pair is reversed, the intersection becomes circular. This can be demonstrated by overlapping the figures at a wider center-to-center spacing. Because only about half of each figure is now involved, the ambiguity is reduced in favor of paraboloids that intersect while facing in opposite directions. The moiré pattern takes the form of circles.

The projection of a sphere resembles that of the paraboloid in that each is an array of concentric circles. In the case of the Fresnel-zone plate, however, all lines and all spacings occupy equal areas, whereas in the case of the spherical projection the equivalent areas diminish from the center to the edge. When a grid is superposed on the spherical projection, the moiré patterns depict the intersection of a sphere by a plane, the angle of intersection being determined by the period of the grid spacing with respect to that of the spherical projection. When the logarithmic grid is superposed on the spherical projection, the resulting moiré pattern indi-

cates two points of intersection as though the sphere were cut simultaneously at two points by a curved knife. One cut appears closer to the equator than the other because the curvature of the "knife" constantly increases. It can also be demonstrated that the cylindrical projection is characterized by similar properties.

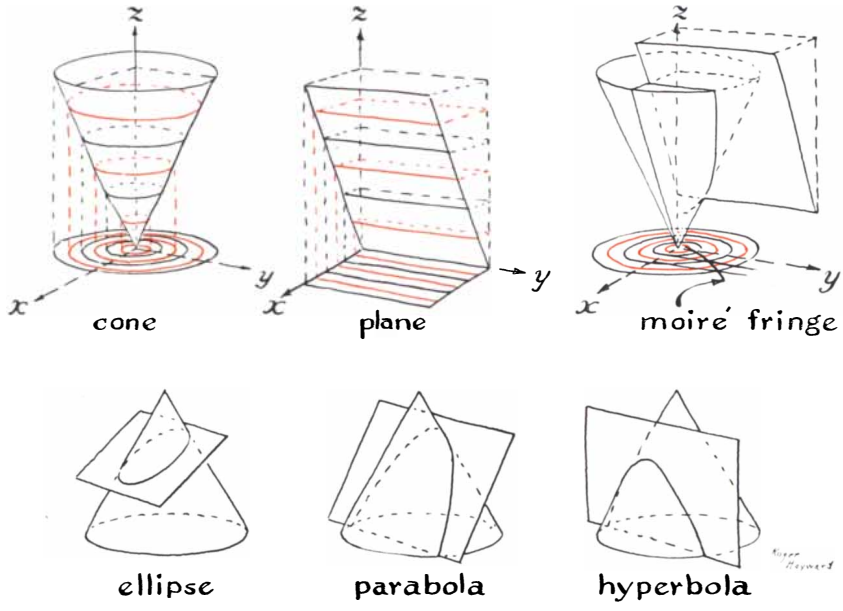
Many natural phenomena can be simulated by the eight repetitive figures. A pair of piano strings that are tuned to the same frequency and vibrate in step, for example, emit a set of sound waves that in some respects is analogous to a pair of grids overlapped so that the lines match. The effect of detuning one piano string can be demonstrated by lifting one grid slightly above its matching print while keeping the lines parallel. The separation has the optical effect of changing the relative period of the grids. Moiré patterns appear in the form of widely spaced fringes, the counterpart of the beat note emitted as the vibrations of the strings alternately fall into and out of step. The spacing between the fringes of the moiré pattern can be interpreted as an amplified copy of the difference in the spacing of the lines constituting the grids. Therefore it can be used as a sensitive measure of the period of either grid if the spacing of one grid is known. If the fringe spacing is designated d and the periods of the grids are respectively a and b, then $d = ab/a - b$.

Straight fringes also appear when the grids overlap at a slight angle. This effect can be employed as a sensitive measure of angular differences. The distance d between the fringes is equal to the quotient of the distance a between the lines of the grating, divided by two times the trigonometric sine of half of the angle θ at which the gratings overlap [$d = a/2 \sin (\theta/2)$]. In the case of the coarse Edmund gratings the line separation, or repeat length of the figure, is .0683 inch. If the transparency overlaps its matching print at an angle of 45 degrees, the fringe spacing is therefore $.0685/2 \times .3827$, or .089 inch. (The sine of 45/2 degrees is .3827.) For angles smaller than five degrees the equation can be approximated to $d \cong a/\theta$, in which the fringe spacing d is approximately equal to the repeat length of the figure a divided by the angle, expressed in radians. (One radian is about 57 degrees.)

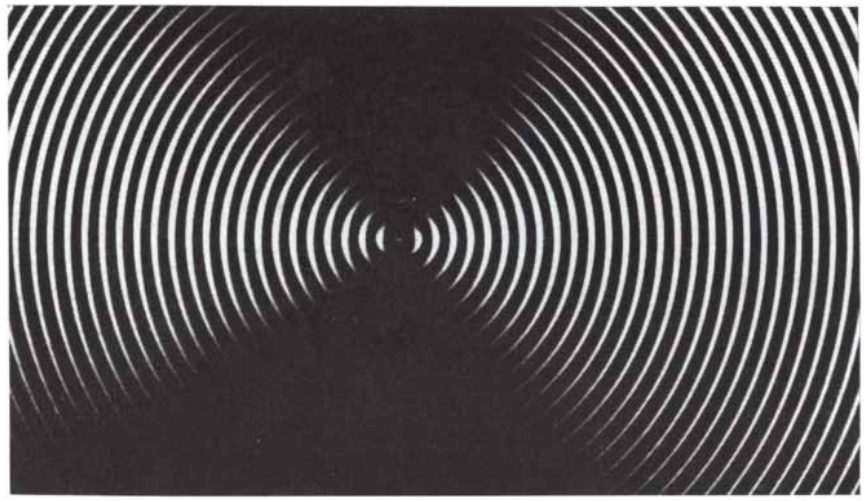
A relatively simple but astonishingly sensitive instrument for measuring small changes in length employs a pair of grids as the amplifying element. According to C. Harvey Palmer of Johns Hopkins University the apparatus can measure changes in rotary motion as small as a billionth of a degree and displacements of a trillionth of a centimeter—less than the diameter of an atom! In an apparatus of simple design light rays from an illuminated grid would pass through a lens and be reflected by a pivoted mirror back through the same lens to focus on a second grid. A condensing lens beyond the second grid would concentrate the light on a photocell. A moiré pattern would appear when the image of the first grid overlapped the second grid. The amount of light reaching the photocell would be determined by the moiré pattern, which in turn would depend on the position of the pivoted mirror, as shown in the illustration on page 142.

This oversimplified apparatus would be sensitive to small changes in the intensity of the lamp, instabilities in the photoelectric circuit and aberrations in the optical system. Such sources of error are balanced out in practical instruments by splitting the light into a pair of compensated beams and illuminating two grids mounted 180 degrees out of phase that energize a pair of photoelectric cells constituting two arms of a Wheatstone bridge. The beams are focused by a well-corrected lens and adjusted for proper phase by a pair of glass plates that can be rotated to alter the effective lengths of the optical paths.

In one experiment made with an easily constructed version of the instrument, Palmer supported the mirror by two wires, one of iron and the other of brass. The wires were surrounded by a small coil of copper wire. When the coil



The moiré effect as interpreted by projective geometry

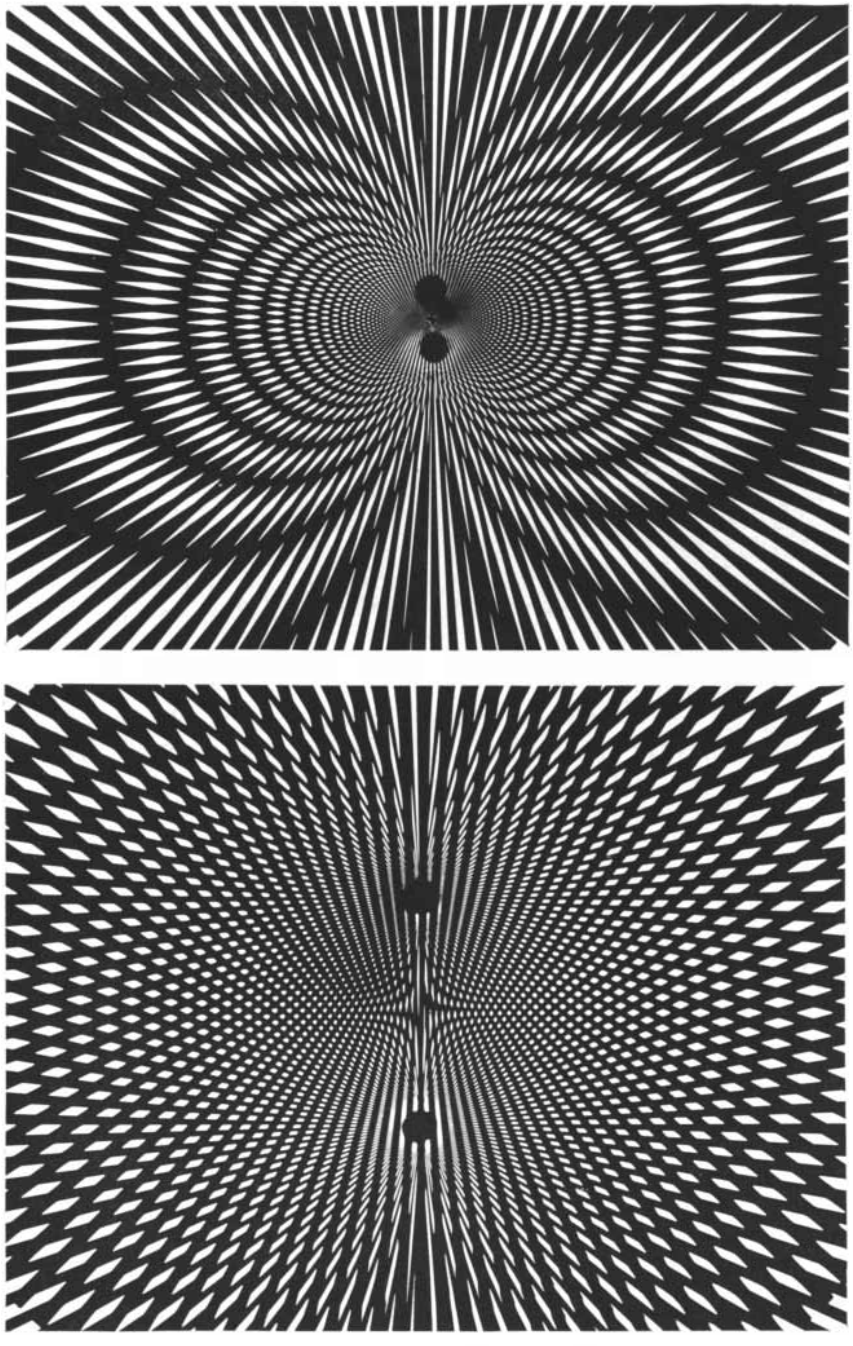


Radiation pattern of a directional radio antenna as depicted by moiré figures

was energized by a flashlight battery, the resulting magnetic field altered the length of the iron wire and rotated the mirror only a minute amount, but enough to send the pointer of the meter off scale!

Amateurs on the lookout for an inexpensive method of measuring the absolute amplitude of microseisms, minute changes in the pressure of a gas, the magnetostriction of solids and so on might well investigate this application of the moiré technique. A practical apparatus of the type, specially designed for amateur construction, is described in the book *Optics: Experiments and Demonstrations*, by C. Harvey Palmer (Johns Hopkins Press, 1962).

Numerous phenomena can be investigated merely by overlapping the repetitive figures. The set of concentric circles, for example, in addition to representing a cone, can be interpreted as a set of concentric waves either radiating from or converging on the center. Because waves of all kinds behave in much the same way the analogue is valid for sound waves, water waves, electromagnetic waves and so forth. Wave interference is easy to demonstrate by overlapping the transparent pattern of concentric circles on its print. Points of destructive interference, where the crest of one wave falls in step with the trough of another, are represented by moiré patterns in the form of hyperbolas. Compare the moiré pattern generated by the pair of concentric-circle figures with the photograph of wave interference in a ripple tank that appears on page 140. The same general equations that predict the behavior of waves in a ripple tank apply when the concentric-circle patterns are used as an analogue computer for investigating wave interference in other media, a subject discussed in this department for October, 1962.



Simulation of potential fields: source and sink **(top); *pair of sources*** **(bottom)**

Conversely, the properties of some materials can be investigated quantitatively by their effect on repetitive figures. The mineral calcite, for example, has the property of splitting light into two polarized components that are physically displaced. The effect can be demonstrated, and the displacement measured, simply by observing a single figure of concentric circles through the mineral. The resulting moiré pattern is a measure of the optical displacement. Spherical waves, such as those emitted in phase by a pair of radio antennas, are also simulated by the patterns. The effect can be studied by overlapping the transparent figure on its print so that the center-to-center distance is less than one interline spacing. The resulting moiré pattern displays two intense beams 180 degrees apart, demonstrating the directional property of paired antennas. When the center-to-center distance is increased, side lobes appear, again as in the case of radio antennas.

The figure composed of radial lines can also simulate a broad class of natural phenomena characterized by potential fields in two dimensions such as the electrostatic force between elements of a vacuum tube or the motion of fluids from an inlet or toward a sink. In the case of a fluid emerging from a port and spreading uniformly over a surface, the radial lines depict the streamlines. Velocity of flow is represented by the spacing between the radial lines; the higher the velocity, the narrower the spacing. The direction of the flow cannot be determined, however, by examining a single pattern, whether the fluid moves toward or away from the center.

What would be the effect of introducing a sink at some point in the field? This rather difficult mathematical problem is easily solved by overlapping the radial print with its transparent mate so that the centers are relatively close. The case of two inlets and no sink can

Republic Aviation's shock tunnel data system uses PB250 computer and Raytheon digital equipment

Raytheon PB computer acquisition creates strong new EDP source

By its recent acquisition of the Packard Bell computer division, Raytheon has clearly announced its intention to become a significant factor in the fields of scientific and real time computers.

Included in the acquisition is one of the most advanced computers currently available to the engineering/scientific community. The Model PB440 is characterized by a unique dual memory stored logic concept which provides unusual operational speed and efficiency as well as unparalleled flexibility. This enables the user to duplicate in one machine the individual capabilities of a number of presently available computers. A second model, the PB250, one of the first solid state computers marketed, is presently used in more than 160 applications and offers low cost, general purpose computation capability.

The combination of Raytheon data processing equipment with PB computers is not as new as the formal organizational merger. For over a year, for example, a shock tunnel automatic recording data system has been in operation at Republic Aviation Corporation which combines a PB250 computer with Raytheon multiplexers, analog to digital converters and power supplies.

Such key elements of scientific data systems have been a part of Raytheon digital product lines for several years. Extremely high speed in their operation, they complement perfectly the similar, extremely accurate equipments acquired from Packard Bell.

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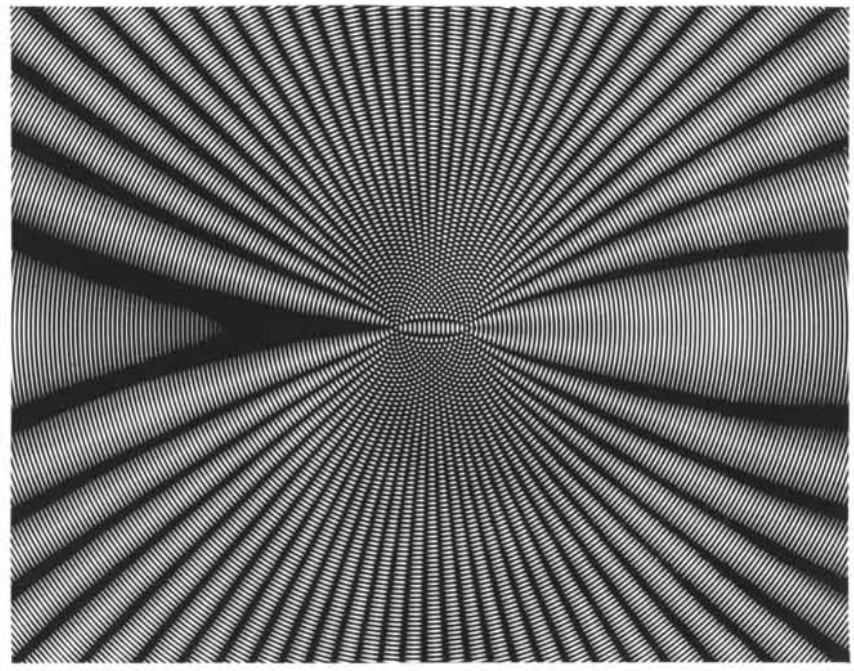
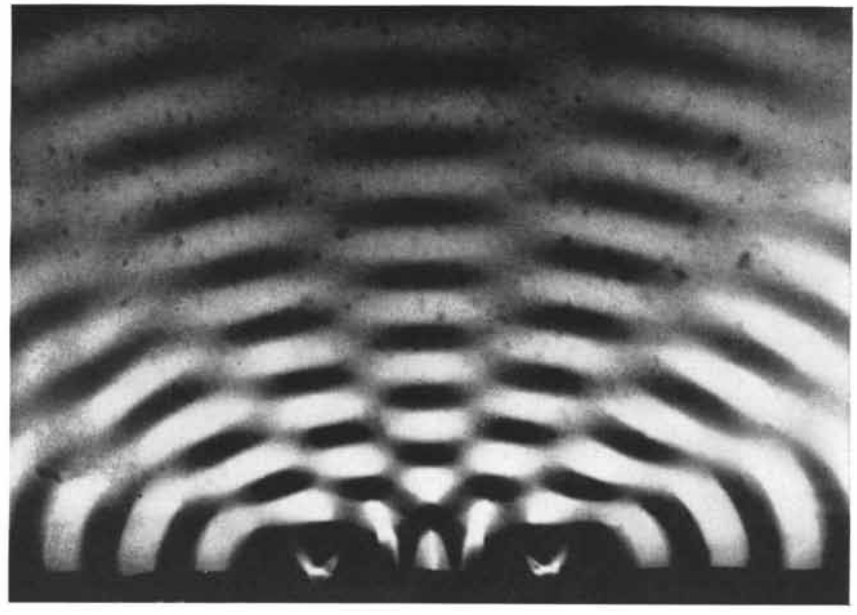


Interference fringes as generated by moiré figures



Interference fringes as generated in ripple tank

be demonstrated by sliding the centers of the figures apart. At a certain distance the pattern displays a "stagnation point," the region of opposing flow from the two inlets.

The parallel straight lines of a grid represent the uniform motion of a fluid, as in the case of an ideal river in which the flow is unperturbed, whereas the logarithmic grid represents uniformly accelerated flow. By overlapping the radial figure with the logarithmic grid the interaction of radial flow and linear accelerated flow can be demonstrated. At points of high linear velocity the stagnation point, indicated by the moiré pattern, moves close to the source of radial flow. The coaxial moiré circles generated by superposing the radial figure on its copy similarly represent, according to Oster, the stress lines in a solid in which the centers of the figures coincide with the locations of applied stress. The patterns also simulate magnetic-field lines between the poles of a horseshoe magnet, just as such lines are conventionally mapped with iron filings.

Why does one see moiré patterns? In

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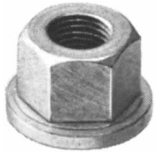
this is one  of them

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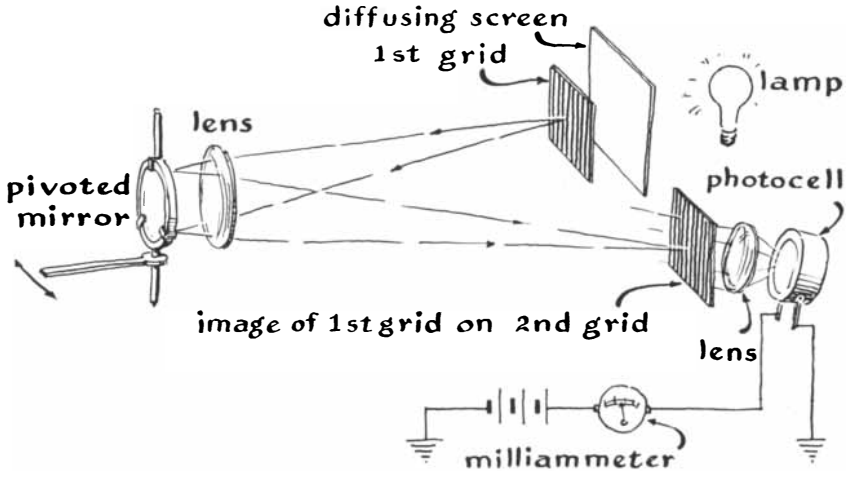
investigating this question Oster devised several experiments that provide clues, if not a definitive answer, to the mystery. "A hint as to what compels us to choose only one type of intersection between lines, the type that we recognize as the moiré pattern," he writes, "can be gained by drawing two straight lines that cross at some small angle. Note the conspicuousness of the intersection, where the lines appear pinched as though two wires had been twisted around each other. The effect is enhanced when the intersection is viewed in red light, diminished in blue light. Evidently the eye is unable to resolve the intersection. When many parallel lines cross, as in the case of two overlapped grids, the eye unconsciously searches the field and ties together these preferred points of intersection. The effect is greatest for lines that cross at small angles.

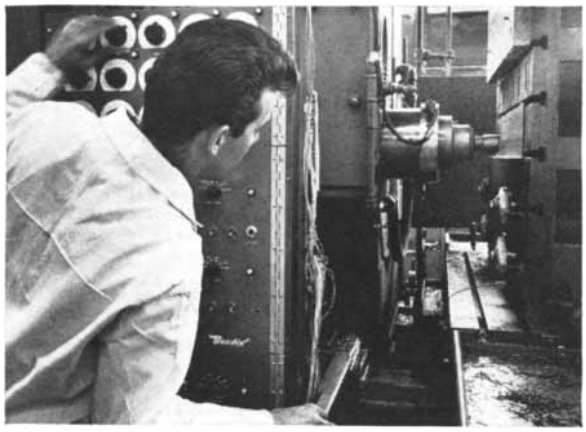
"To examine the effect of intersections in another way, lay a hair on a grid of 65 lines per inch. (Preferably this should be a red hair; it is finer than a blond or brunet one.) Neither the hair nor the rulings can be resolved if the combination is examined at arm's length. Yet the points of intersection between the hair and the rulings will stand out clearly as a line of dots. Incidentally, the dots constitute a direct measure of the first derivative, or slope, of the curve described by the hair. Conversely, as readers familiar with the calculus will recognize, for a dot distribution that follows a certain function the curve of the hair is the solution of the first-order differential equation.

"Many effects can be seen by close observation of single patterns, preferably figures printed on a white background. When the print of the radial figure is examined by one eye at a distance of less than 10 inches, a gray, blurred pattern is observed. The blur arises from the inability of the eye to focus properly at short range on the moiré pattern that develops when the radial figure and its afterimage register on the retina. Other interesting effects appear when the eye is fixed on a pattern that moves. For example, if the coarse-line figure is held by diagonally opposite corners and rocked, a dark bar will link the grasped corners, flanked on each side by curved bars in a lighter tone. Again, this moiré arises from the intersection at a small angle of the immediate image of the grid on the retina and its afterimage. Observe any of the centrosymmetrical figures while you hold it steadily in your hand and move your hand in a circle. Moiré patterns will be seen that arise from the interaction of the immediate images and afterimages and will appear to rotate in step with the movement of the figure.

"It is even possible to see colors by staring at the black and white prints, particularly when attention is fixed on the strongly illuminated center of the radial figure. Various individuals report different colors. I see mostly gold and pink. In addition to appearing colored, the central portion of the circular pattern appears to be in rapid rotation. Children see the effects readily and many adults do not. These effects are intimately tied up with the granularity of the retinal receptors, with the cones of the fovea and also with the rapid involuntary movements of the eyeball—the saccadic movements and tremors. It is conceivable that the fovea acts as an almost unperceived circular figure superposed on our vision, but we are so accustomed to its presence that we do not notice it."



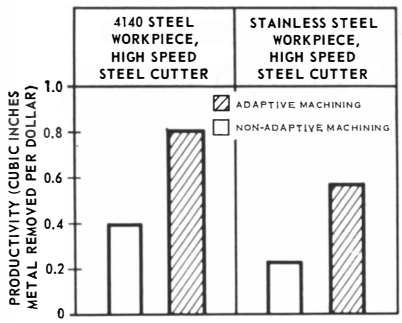
Schematic arrangement of simple moiré apparatus for measuring distances and angles



Adaptively Controlled Machines For Improved Productivity

The need for adaptive control in the metal-cutting process is evident when one considers the present methods used to select metal-cutting parameters. This generally consists of reference to machinability data published in handbooks, augmented by past experience of the operator. Because of the wide variations which occur in machine operating costs, machine rigidity, workpiece metallurgy, and so forth, the handbook values cannot adequately represent a specific cutting situation. In order to optimize productivity it is necessary to perform an extensive series of trial-and-error tests. These tests may lead to a particular set of cutting parameters which optimize a given situation, but even this is not entirely satisfactory because there will always remain unpredictable variations which occur during the cutting process. A good example of this is the dulling of a tool as cutting is in progress. Even if the initially selected cutting parameters are nearly optimum, the gradual change in tool sharpness will cause the performance to gradually depart from the optimum.

The Bendix Research Laboratories Division began work on the development of adaptive control techniques for numerically controlled milling machines in June 1962, under the sponsorship of the Advanced Fabrication Techniques Branch of the Air Force Materials Laboratory. The project culminated in the construction and test of a prototype adaptive control system operating in conjunction with an actual numerically controlled milling machine. Performance evaluation tests made with this prototype system over a limited range of cutting conditions have shown that adaptive control can provide very substantial improvements in the productivity of such machine tools.



Productivity comparison of conventional machining & adaptive controlled machining.

Test results for two typical combinations of tools and workpiece materials are summarized in the chart, which compares average productivity with and without adaptive control. As indicated, the use of adaptive control enabled significant cost reductions due to increasing the productivity of the machine tool. The same concepts developed for milling machine control can be applied to a variety of diverse manufacturing systems, and to complex military and process control situations having the basic requirement of optimal selection of multiple control parameters.

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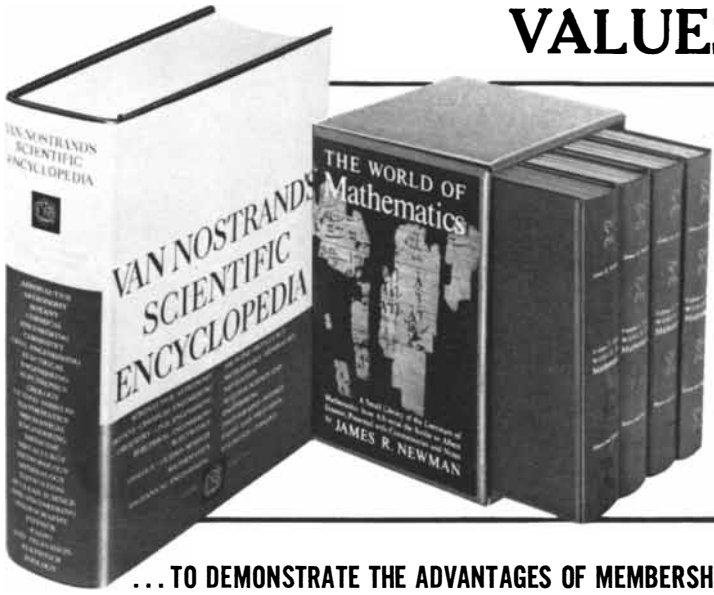

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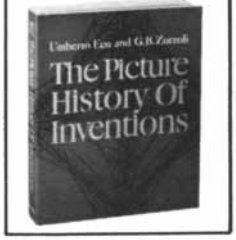

BOOKS

Arthur Koestler's view of the creative process

by George A. Miller

THE ACT OF CREATION, by Arthur Koestler. The Macmillan Company ($8.95).

Creativity is "in." Everyone is talking about it. Educators are trying to recognize it, psychologists are trying to measure it, businessmen are trying to buy it, foundations are trying to support it, and in this large, untidy book Arthur Koestler is trying to explain it. Koestler's contribution is 750 pages diagnosing creativity as the recognition of a common element in two habitually incompatible frames of reference. (As a sign of changing times, his presentation of the same idea in 1949 was entitled *Insight and Outlook*.)

The value of creativity must have been recognized long ago; why is it currently stirring up so much dust? I know of no evidence that interest has been stimulated by recent breakthroughs in psychology, so I assume that this interest is an intellectual fad. Whether it develops into anything more will depend on the success of efforts to formulate a coherent hypothesis and program of research. That is what Koestler hopes to provide in *The Act of Creation*.

Koestler has written two books in one. Book One follows *Insight and Outlook;* creativity is much the same everywhere—in humor, science, art. Our knowledge and skills are organized according to rules into autonomous, coherent subsystems that Koestler calls "matrices." These matrices represent habitual responses to routine problems; our minds normally function by the association of elements within a single matrix. Sometimes our habitual associations are "blocked." Unblocking requires that we recognize some element as the same (or similar) in two different and previously unrelated matrices; Koestler calls this recognition "bisociation." Bisociation creates an analogy that may be amusing, enlightening or inspiring according to its emotional context, and it enables us to bring a new matrix of skills to bear on a problem. Because bisociation cuts across habitual modes of thinking, we cannot make it happen, but we can let it happen by relaxing our conscious awareness of the rules, as we do in reverie or sleep. The argument is developed by examples of the most diverse sort; jokes, scientific discoveries and artistic works are all described as bisociated matrices.

Book Two moves toward the same conclusion by a different route. Evidence from biology and psychology is marshaled to argue that all life processes, from the synthesis of proteins through our social institutions, are hierarchical. At any level in the hierarchy the subsystems look like units to the level above but are each complex matrices relating units on the level below. The constructive aspect of this argument is somewhat obscured by Koestler's impatience with behavioristic psychology, but one gathers that he believes the normal functioning of the hierarchy of matrices leads to curiosity, exploration and combinatorial play as activities valuable in their own right, and so it is possible for creativity to triumph over habit. In the last five chapters this hierarchical system is said to imply a theory of thinking in which bisociation is an essential process.

Koestler's position on the psychology of scientific thinking is well known. There is, he says, a large component of irrationality in even our most rational achievements. Behind the logical façade boils a witch's brew of prejudice, blindness, passion and envy. In *The Sleepwalkers,* for example, he reviewed the rise of modern science from Copernicus to Newton and concluded: "The muddle of inspiration and delusion, of visionary insight and dogmatic blindness, of millennial obsessions and disciplined double-think, which this narrative has tried to retrace, may serve as a cautionary tale against the *hubris* of science—or rather of the philosophical outlook based on it." To deny the irrational component of creative thinking, Koestler believes, broadens an unhealthy gap between the intellect and the soul of modern man.

The Act of Creation builds this position into a psychological theory, and it represents Koestler's claim to be considered as a scientist as well as a novelist and an interpreter of science. Because he comes down so heavily on the side of the mental devils, his arguments cannot avoid giving offense to those who believe irrationality is the enemy, not the source, of creative thinking.

What makes some thought creative? Koestler assumes that the extra something in creative thinking is psychological, which is a questionable assumption in itself. If I, in 1964, recapitulated in every detail Newton's thought processes, they would no longer seem creative. The same psychological operations can be creative in one social situation and not in another; I have always understood this to mean that the definition of creativity is as much a sociological as a psychological problem.

To a psychologist, what Koestler calls the Eureka experience is just as likely to be a false insight as a true one. Koestler knows this, but he does not conclude that no amount of psychological analysis can distinguish creative bisociation from uncreative. Years of effort may be needed before we know if a sudden flash was creative; no psychological theory could predict the outcome. Koestler the historian talks about real creativity, but Koestler the psychologist talks about something he calls subjective creativity, the impression one has of being creative. This is not as much of a retreat as it may seem; certainly our subjective impression of creativity, right or wrong, is our best altimeter for climbing scientific mountains. It does, however, place a qualification on any claims for what a psychological theory can accomplish.

Although *The Act of Creation* is a contribution to the psychology of thinking, Koestler's views are shaped more by his studies of the history of science than by his study of psychology. He does not review current work by psy-

chologists: no mention is made of research by Jacob W. Getzels and C. Wesley Jackson on creativity in children, of factor-analytic studies by J. P. Guilford and his colleagues, of studies of creative personalities by Donald W. MacKinnon, Frank Barron, Anne Roe and others, of Allen Newell and Herbert A. Simon's simulations of cognitive processes, of work by Carl I. Hovland, Jerome Bruner and others on concept learning, and so on through the basic bibliography of the field. Instead Koestler digs into psychology's past and comes up with the "schools" that were so influential in the 1920's and 1930's: behaviorism, Gestalt, psychoanalysis.

To appreciate the psychological landscape on which Koestler is working we should look briefly at some of these traditional positions. The full spectrum of psychological thinking about thinking includes all hues of the rainbow, but given a little expository license it is possible to recognize five primary colors from which the rest can be derived.

First there is the view that creative thinking is logical thinking. The central assumption is that only one attribute of thought is significant for the advancement of knowledge, the attribute of *truth*. Anyone who considers the role of logic and mathematics in science must recognize the power of this assumption. Unfortunately, as a psychological description of the creative process this view has serious defects. Logic is a method of verification, not a method of discovery. When we ask how a scientist hits on the hypothesis from which he deduces consequences and for which he induces evidence, we find that logic is simply inadequate to describe what actually occurs.

A second approach is associationism. According to this ancient doctrine the mind grows by forming *connections*. Originally the things connected were ideas; today they are stimuli and responses. The bonds are established through experience, and the most creative mind is the one with the largest store of connections among which to select. Education, both formal and informal, is indispensable, and the ability to form and use connections—an ability we can measure with mental tests—holds the key to the act of creation. This, however, cannot be the whole story. Some associations can become so entrenched that they actually inhibit our appreciation of novelty. When we ask how scientists rise above habitual modes of association to discover something new, associationist theory has little more than probability as an answer.

The configurational approach, advocated by Gestalt psychologists and developed most explicitly by Max Wertheimer, rejects the idea of associative chains that poke randomly into dark corners of the mind and proposes instead that thinking is a guided process of restructuring a problem situation until it takes on the *configuration* of a solution. Transformations are guided by insight—by a grasp of the cognitive geography of the problem—and by some conception, however hazy, of the attributes any solution must have. By comparing initial and final configurations a thinker is led to focus on trouble areas, which he tries to eliminate or circumvent. For problems that can be characterized as a search for a path from a given to a desired situation, the Gestalt approach is extremely suggestive. The universality of this type of problem, however, has been questioned by many critics.

Koestler's views fit best into a fourth category that has appealed to many psychologists in recent years, a category that might be loosely termed psychodynamic. This approach is associated most closely with the name of Sigmund Freud, although it has a long history among Romantic philosophers. The burden of creativity is shifted to the *unconscious* mind, where ideas can move and mingle as they will, free of the constraints of logic or habit. The history of science supplies many examples of unconscious work—in dreams, reveries, imaginative play—and great ideas seem to pop into great minds at the most bizarre and unexpected moments. Freud's comments on the psychodynamics of genius and its relation to neurosis are scattered through his works and do not give a clear picture of the creative process, but Ernst Kris has developed and supplemented them in his theory of ego regression. Faced with a problem, a creative thinker may regress to an earlier stage in which the problem was more fluid, then impose a fresh structure on it that enables him to formulate it more productively. Critics of this view say that to turn creativity over to the unconscious is to abdicate scientific responsibility for explaining it. The unconscious is a name for all those processes we assume must go on but of which we have no conscious awareness. To locate a process there is very different from understanding it.

Finally, a new approach has grown up recently around the digital computer. Various names have been suggested —cybernetics, information processing, artificial intelligence, computer simulation—each with its own flavor and emphasis. Let me group these as the "generative approach," by which I mean that they describe thinking in terms of *rule* systems. By following the rules the performance in question can be generated as one of an infinite variety of performances admissible under the rules. The rules characterize what the system knows; the way these rules are actualized characterizes what the system does. The rules are not necessarily rules of logic; various strategies, or "heuristics," may be available for different types of problem. There is no guarantee that heuristic rules will provide a solution; many involve a cognitive gamble. So diverse and flexible are the available heuristics that already advocates of this approach maintain that they can account for any problem-solving performance that human beings are capable of generating. Critics reply, however, that the generative approach is better at solving problems than at finding problems worth solving.

With all these theoretical resources at our disposal, our task is to adjudicate among them. Each represents a partial insight into some aspect of the total process. The trick is to blend them into a coherent and pleasing whole. Let us examine Koestler's blend in these terms.

First, logic. One gets an impression that Koestler distrusts logic; it operates within a well-defined frame of reference and may inhibit illogical but creative bisociations with other matrices. He does not say explicitly that logical thinking is a handicap to the creative thinker; I get my impression less from what he says than from the way he says it. In his own attempt to contribute creatively to science, Koestler does not begin with definitions and axioms from which theorems are logically derived. Instead he insinuates his philosophy into the reader's mind by anecdotes, slogans, examples, metaphors. In neglecting logical arguments Koestler is consistent with his own theory. Instead of logic he provides a steady flow of fresh analogies and similitudes that carry the reader along with a feeling of comprehension but often leave him finally wondering exactly what he comprehended. My conversation has been much enriched by reading *The Art of Creation*, for which my friends are probably grateful, but I am still unsure about the vectorial resultant of all these interesting bisociations.

Koestler's bisociative process produces not logic but analogy. More precisely, for Koestler creative thinking is both prelinguistic and prelogical; its

manifestation on the symbolic level, however, is more often metaphorical than logical.

Of associationism Koestler holds much the same opinion as he does of logic. Association is something that occurs within a single matrix. When it sparks across matrices, it is qualitatively different and must be called bisociation. Bisociation is first introduced to characterize humor. A story is funny if the punch line suddenly shifts a listener's thoughts out of one frame of reference into a new and unexpected frame. Although alternative hypotheses are available, Koestler's explanation of the comic seems at least reasonably clear and intelligible.

As the book proceeds, however, Koestler casts his net into deeper and deeper waters. First he extends the theory to describe discovery as well as appreciation, at which point bisociation becomes fuzzily unconscious. Soon we hear that it characterizes the general evolution of ideas, that blocked matrices and bisociation are cultural as well as psychological phenomena. Next the fine arts are drawn into the discussion, and in Book Two the same ideas are used to unify all levels of biological and psychological science. Each broadening costs something in precision, until in the end we are left with little more than an ideology, somewhat reminiscent of Hegel's, but with thesis-antithesis-synthesis translated into $matrix_1$-$matrix_2$-bisociation.

Personally I find it difficult to understand the difference between association and bisociation. Consider an example: Professor Jones is coming to visit; I try to remember who is around who might enjoy him; I think of Dr. Smith. Was this association or bisociation? I would have called it constrained association, but it fits all the criteria for bisociation: $matrix_1$ consists of my associations with Jones; $matrix_2$ consists of my associations with people I work with; Smith was an element common to both.

But if this banal operation of thought is bisociation, wherein lies its creative potential? Something more is needed, but what? Not emotion. Had I been happy or angry about Professor Jones it would not have endowed my bisociation with any creative flame. Nor would it have been more creative if the idea had come to me in a dream. Koestler recognizes this need and tries to meet it:

"Minor, subjective bisociative processes do occur on all levels.... But objective novelty comes into being only when subjective originality operates on the highest level of the hierarchies of

existing knowledge.... A further criterion of the creative act was that it involves several *levels of consciousness*.... The restructuring of mental organization effected by the new discovery implies that the creative act has a revolutionary or *destructive* side."

Now, however, we have lost touch with the starting point. The creative spark in humor surely does not involve the highest level of knowledge or require any revolutionary destruction of mental organization. The distinction between association and bisociation has lost its importance; the focus has shifted elsewhere.

So the position of association in Koestler's theory is not entirely clear. What is clear, however, is that Koestler *thinks* bisociation is very, very different from association; otherwise his violent attack on the behaviorists would be incomprehensible. Attacks on stimulus-response theories (which represent modern associationism) are of course nothing new. When one attacks strict stimulus-response behaviorism these days, one is on the side of the big battalions. Yet Koestler writes as though it were still the 1930's and behaviorism were in its prime. In 1964 most psychologists who still work in this tradition have introduced hypothetical mechanisms to mediate between stimulus and response. *They* think they are working on exactly the kind of processes Koestler calls bisociation; they are sure to be angered by Koestler's sarcastic misrepresentation of the current situation, and I cannot say that I blame them.

As for the Gestalt approach, Koestler addresses a chapter to what he calls "The Pitfalls of Gestalt." The pitfall turns out to be the emphasis Gestalt theorists place on visual perception. The discussion of Gestalt is not really to the point, however, since Koestler refers only to a study of apes written by Wolfgang Köhler in 1918 and one or two of the problems used by Carl Duncker and Norman R. F. Maier in the 1930's. The pivotal work by Wertheimer is not mentioned, so it is impossible to say where Gestalt ideas might fit into Koestler's theory.

As I have indicated, Koestler favors a psychodynamic approach and endows the unconscious with wondrous powers. He knows that Freud was thinking along the same lines, of course, but his bibliography is quite bare of more recent contributions. Kris, Lawrence S. Kubie, Ernest Schachtel and D. Rapaport, for example, are not mentioned, although their ideas are directly relevant. This contrasts poorly with Koestler's apparently extensive research into the history of science.

As for the generative approach, I suspect Koestler must have found himself in a dilemma. He obviously likes the idea that matrices can be codified by rules: he mentions it repeatedly throughout the book. The notion of hierarchies, which plays an important role in Book Two, also pleases him. So he must have been sorely tempted by generative hypotheses, which make good use of the fact that rules can be represented by instructions to a computer and that programs of instructions for serial computers necessarily have an elaborate hierarchical structure. On the other hand, there is no obvious place in generative theories for the distinction between conscious and unconscious processes that plays such an important role in psychodynamic theories. And the possibility of turning it all over to a machine is clearly repugnant to anyone with Koestler's humanistic vision of mental life. With respect to generative theories, he borrows but does not subscribe.

When we try to put Koestler's theory into the perspective provided by other philosophers and psychologists, then, we find much to criticize. He has not come to grips with current psychological thinking, he repeatedly creates straw men for the sole purpose of knocking them down, he introduces new terms for old ideas and draws distinctions that seem clear at first but prove on examination to be operationally undefined, he substitutes bisociation for reasoning and anecdotes for evidence, he stretches his ideas further than they can go, he repeatedly proclaims the obvious as if he were the first ever to think of it. A scientist who reads the book as a scientific treatise will find it an irritating and pretentious performance.

In the preface Koestler says that he knows his theory "will suffer the inevitable fate of being proved wrong in many, or most, details." I doubt if it will. Whereas a good scientific theory is exquisitely fragile, it is difficult to think of anything that could shatter Koestler's. It has the kind of elastic incorrigibility that makes a theory extremely tough. For example, in a theory that focuses specifically on the synthesis of matrices it might be supposed that any evidence for the creative use of analysis—resolving confusion by the discovery of a crucial distinction—could be considered as disconfirmation. But not so. Were I Koestler, I would reply that the old distinctions constituted $matrix_1$, the new distinction was $matrix_2$ and the creative act was the bisociation of the two into a new cognitive synthesis including them both. I have tried to imagine other lines of attack, but the theory seems more resilient than I am imaginative. I conclude that Koestler's theory is a contribution to philosophical psychology.

If I read Koestler's theory as philosophy, I can be somewhat more generous, since I am not a philosopher. I can admire Koestler's courageous attempt to clean out what obviously seem to him to be the Augean stables of psychology. I share most of his prejudices and approve of most of his aims. If he flies too high and handsome at times, perhaps we should not try to bring him down to earth; perhaps we should offer him flight pay. The general intent of his argument is not bad when compared with other discussions of the same topic, and he finds a place for most of the important ideas, even though the relations among them are not always clear. Seen in terms of what he was trying to accomplish, the book has considerable merit. Yet, just because I do approve of his good intentions, I am all the more disappointed that he did not present a stronger scientific case for them.

There can be no doubt that Koestler has a genius for analogy, that bisociation is a process at which he excels. He is never at a loss for an analogy to make the strange seem simple and familiar, which is one source of his great skill as a popularizer of science. As a technique for advancing science, however, analogy is insubstantial and unsatisfying. Instead of learning something new, we are told that we really knew it all along but in a different context.

Analogy is infectious, so perhaps I can be forgiven if I conclude with one of my own. Goethe, like Koestler, was a scientific amateur with a distrust of logic and an aggressive faith in the validity of intuitive observation and analogy as the primary sources of truth about life in general and science in particular. He also tried his hand at psychology. The topic that captured Goethe's imagination, however, was the perception of color. In 1791–1792 he published two monographs; then in 1810 he brought out a two-volume book, *Zur Farbenlehre*. The useful part was its description of many subjective phenomena of color perception, but it also contained a theory. According to Goethe's theory—I rely for details on Edwin G. Boring's *Sensation and Perception in the History of Experimental Psychology*—color vision is based on a polarity between yellow and blue. This was elaborated with much argumenta-

tive detail and illustrated by analogies: yellow is to blue as brightness is to darkness, as light is to shadow, warmth to cold, active to passive, force to weakness, repulsion to attraction, proximity to distance, acid to alkali. Thus the theory was extended and made to integrate a variety of perceptual and conceptual phenomena.

If there had been any behaviorists, Goethe would surely have assailed them just as Koestler does today. Since there were none, Goethe's scorn was turned on Newton, whose theory that white is a mixture of colors seemed absurd—in flat contradiction to the facts of ordinary observation. (Hermann von Helmholtz attributed the violence of Goethe's disgust to his poetic temperament, which is as charitable an interpretation as any.) Goethe obstinately opposed the Newtonian theory, which was correct, and defended his own intuitive theory of polarities, which was not. He was far too important to be ignored, so his ideas were cited in all the texts for the next 50 years.

I know that analogies, even multiple analogies, can be dangerously misleading, so I must hasten to add that in drawing this one I have *not* said that Koestler's theory of creativity is as sterile as Goethe's theory of color, or that behaviorists today are as right as Newton surely was then. The possibility is nonetheless worth considering.

Short Reviews

A HISTORY OF DOMESTICATED ANIMALS, by F. E. Zeuner. Harper & Row, Publishers ($12). A lavishly illustrated, uncommonly interesting account of man's use of animals. Domestication probably began with dogs in the Mesolithic, around 8000 B.C. The theory has been advanced that from the beginning animals were deliberately domesticated to satisfy such human needs as food, shelter, clothing and animistic ceremony. Zeuner holds that this view is less supported by evidence than the one that domestication was a spontaneous phenomenon involving adaptation to environment, interaction of groups of men and certain species of animals, and dominance of the more intelligent group. "As a rule," he says, "the social evolution of a species must have reached a certain level before domestication becomes possible." With the notable exception of the cat all domesticated animals have in the wild state a social life of some kind, forming packs or herds.

It is likely that long before the Meso-

lithic, man kept young animals as pets. The ability to get along with other species is not confined to man: friendships between cats and dogs and between cats and tamed birds under conditions of domestication are common enough. Once the practice of having pets is culturally ingrained, the enlargement of such relations to embrace a pack of dogs or a herd of sheep or reindeer is not surprising. A kind of symbiosis arises in which the host is the exploiter, but the guest derives substantial benefits by way of food, protection and so on. Ultimately the guest may have to yield up its carcass to satisfy the host's needs. Domestication moves from loose contacts to confinement, to breeding in captivity, to selective breeding organized by man to obtain certain characteristics and finally to the planned "development" of breeds with certain desirable properties. Dogs, reindeer, goats and sheep were domesticated in the preagricultural phase; later the crop-robbers such as cattle, buffalo, yaks and pigs were brought under dominion. A higher stage is marked by the enlistment for transport and labor of elephants, horses, camels and asses. The mongoose, the ferret and the cat were pressed into service as pest-destroyers, and various other mammals such as the rabbit, the dormouse, the hyena, the gazelle, the ibex, the mouse and sundry species of birds, fishes and insects have at different times been brought under conditions of domestication for reasons ranging from the need for food to the pleasure of their company. Zeuner considers each of these groups and reports innumerable fascinating details about the methods of domestication, the objectives sought, the effects on the animals themselves, the breeding of species for sport, beauty and whatnot. An altogether engrossing volume.

FIFTY YEARS OF X-RAY DIFFRACTION, edited by P. P. Ewald. N. V. A. Oosthoek's Uitgeversmaatschappig Utrecht ($12). This book is connected with the celebration at a commemoration meeting in Munich in 1962 of the 50th anniversary of Max von Laue's discovery of the diffraction of X rays by crystals. It contains a number of articles by the world's leading crystallographers describing both the state of the discipline today and the contributions scientists in many lands have made to this fruitful and widely connected branch of knowledge. In addition to the excellent articles explaining the principal methods and problems of crystal-structure analysis and the impact of X-ray diffraction on physics, there is a fine autobiographical piece by von Laue that his tragic death prevented him from delivering in person at the meeting, articles about such pioneers as W. H. Bragg and C. M. Paul Knipping, and some 30 personal reminiscences by, among others, E. N. da C. Andrade, W. L. Bragg, Kathleen Lonsdale, Linus Pauling and Michael Polanyi. This is a book to give much pleasure to scientists, historians of science and educated readers who care about the panoramic spectacle of the growth of a brilliant idea. Illustrations.

HISTORY OF SCIENCE: ANCIENT AND MEDIEVAL SCIENCE, edited by René Taton. Basic Books, Inc. ($17.50). This volume, which covers the history of science from the beginnings to 1450, is the first installment of a translation from the French of an ample, scholarly survey published a few years ago. The contributors, with one or two exceptions, are French specialists in different branches and periods of the history of science. The book has been much praised, and nothing further need be said on this score in a brief notice. One may be permitted to observe, however, that a cooperative history of this kind, although nothing better can be found, is inevitably much less satisfactory than history seen through the prism of a single mind. By "less satisfactory" is meant not less comprehensive or accurate but less readable, less exciting intellectually and less able to convey a unified impression of the growth of ideas. Many illustrations and good bibliographies.

SHAKESPEARE IN HIS OWN AGE, edited by Allardyce Nicoll. Cambridge University Press ($9.50). As marvelous as Shakespeare is, it is getting harder and harder on this 400th anniversary of his birth not to feel that one is almost drowning in the printed matter that keeps pouring out to celebrate the event. The present volume, which is the 17th in the established series called "Shakespeare Survey," deals with many facets of Elizabethan life during the period in which Shakespeare's genius presided. Among the topics discussed in some 28 essays is the environment of Shakespeare's time—city and country, the daily life of various people from sailors to lawyers, scientific thought, medicine and public health, actors and theaters, music and ballads, the printing of books. Written by specialists, the pieces are of course authoritative, but many are simply pedantic. The collection as a whole is not an exciting contribution to one's understanding of Elizabethan times. Illustrations.

CONVERSATIONS WITH CARL JUNG AND REACTIONS FROM ERNEST JONES, by Richard I. Evans. D. Van Nostrand Company, Inc. ($1.75). This paperback is a transcript of Evans' filmed interviews with Jung in Zurich just before his death in 1962. The dialogue afforded Jung an opportunity to reflect on his contributions to psychology, psychoanalysis and psychotherapy over a period of some five decades and also to give his opinions about conceptual differences with Freud and others. Included is a transcript of another filmed interview with Ernest Jones, Freud's loyal follower and biographer. Whether or not one is a Jung enthusiast, one picks up this little volume with some excitement and anticipation. The result is disappointing. On the whole the dialogues are a bore, neither incisive in their questions nor refreshing in their responses.

PSYCHOLOGY IN THE MAKING: HISTORIES OF SELECTED RESEARCH PROBLEMS, edited by Leo Postman. Alfred A. Knopf ($9). Thirteen authors present historical accounts of particular topics that are of present interest in psychological research, to wit brain localization, hunger and thirst, inheritance of behavior, inheritance v. learning in perception, reward and punishment in learning, memory for form, the nature of intelligence, clinical v. statistical prediction, mammalian sucking, repression and hypnosis. Preceding these accounts there is an excellent chapter on the nature of the history of science, the reasons for studying history, the factors that facilitate and that hinder scientific advance, and the characteristics of the scientist. History may be a description either of what the past was like or of how the present got to be the way it is, and these chapters are very much of the latter kind, starting, except for casual mention of the ancients, with Charles Dumas on hunger in 1803, Franz Joseph Gall on phrenology in 1810, Charles Darwin on instinct in 1859 and Sigmund Freud on repression as late as 1893, and running on up to a culmination of a multitude of researches in the 1950's. Most historical accounts begin to falter 20 years before the date of writing and do not dare to touch the current decade, but these excellent systematic discussions are not really histories; rather are they discussions of recent progress in 11 active fields. Any chapter will provide a young instructor with his

outline for eight or 10 lectures, and he who browses at the edges of new research will find each of them interesting.

THE SHERPAS OF NEPAL, by Christoph von Fürer-Haimendorf. University of California Press ($6.50). An anthropological study of these warm, cordial, cheerful Buddhist highlanders whose settlements lie at an average altitude of 12,000 feet in a number of narrow valleys surmounted by some of the world's highest peaks, including Everest and Lhotse. Among the topics treated are environment and economy, family life, village organization, monastic institutions, the practice of religion, values and moral concepts. The Sherpas are celebrated for their services as porters and guides in mountaineering expeditions, but little is widely known of their society, their way of life and their many admirable personal traits—a gap in knowledge that this book substantially narrows.

CHALLENGING MATHEMATICAL PROBLEMS WITH ELEMENTARY SOLUTIONS, by A. M. Yaglom and I. M. Yaglom. Holden-Day, Inc. ($5.95). This is the first of a two-volume translation and adaptation of a Russian problem book. The problems in this volume have to do with combinatorial analysis and probability; they are not elementary and the solutions are not easy.

THE CRITICAL APPROACH TO SCIENCE AND PHILOSOPHY, edited by Mario Bunge. The Free Press of Glencoe ($9.95). A collection of 29 essays presented in honor of the British historian and philosopher of science Karl R. Popper on his 60th birthday. Many of the essays are concerned with technical aspects of Popper's thought, particularly with his somewhat overpraised notion of falsifiability as the touchstone of useful scientific systems and theories.

THE HUBBLE ATLAS OF GALAXIES, by Allan R. Sandage. Carnegie Institution of Washington ($10). A splendid collection of astronomical photographs, superbly reproduced on large pages (15 by 11¼ inches), representing the work of more than four decades on Mount Wilson and on Palomar Mountain. The atlas contains views of 176 galaxies selected to elucidate the classification scheme devised by Edwin P. Hubble, who proved in the early 1920's that galaxies are great collections of distant stars—"island universes"—and not nearby nebulosities. Hubble had planned this atlas and had begun assembling

notes for it before his death in 1953. The task was taken up and completed by his colleague Allan R. Sandage. A valuable reference work as well as a breathtaking view of the universe as it has been revealed by the largest telescopes.

THE MECHANICAL TECHNOLOGY OF GREEK AND ROMAN ANTIQUITY, by A. G. Drachmann. The University of Wisconsin Press ($6). A survey of the literary sources—primarily the *Mechanics* of Hero of Alexandria—of the mechanical technology of the Greeks and Romans, which included toothed wheels, the lever, the pulley, the wedge and of course Archimedes' superlative endless screw: the combination of a screw and a toothed wheel. Many illustrations reproducing the original manuscript figures.

SPACE SCIENCE, edited by Donald P. Le Galley. John Wiley & Sons, Inc. ($17.50). Papers on space exploration, stellar evolution, the physics of the sun, the origin and evolution of the solar system, radio astronomy, space probes, cosmic rays, the exosphere, rocket spectroscopy and related subjects. Designed to furnish space scientists and engineers with a summary of the theoretical and experimental findings of the first five years of the space age. Illustrations.

SUTTON HOO, by Charles Green. Barnes & Noble, Inc. ($7). An able and readable account for nonspecialists of the 1939 excavation of a royal ship burial at Sutton Hoo. In addition to describing the digging and the contents of the ship, the book discusses a number of intriguing questions such as the identity of the king who was buried with the ship, the provenance of the beautifully wrought jewelry, silver-plated armor and other objects, the methods of shipbuilding, the routes probably followed by North German pirates and settlers in crossing the North Sea from the Continent to Britain, and the consolidation of the Wuffa East Anglian dynasty to which the king appears to have belonged. Illustrated with photographs and many drawings.

FOCUS AND DIVERSIONS, by Lancelot Law Whyte. George Braziller ($5). The autobiography of a British writer who has also given his time to teaching, industry, banking and manufacturing (for example Power Jets, Ltd., which made the Whittle jet engine). Whyte is not without imagination, but his philosophical speculations about science are grandiose and invariably beyond his own grasp, and he is an incorrigible name-dropper.

A STAR CALLED THE SUN, by George Gamow. The Viking Press ($5.75). A successor to Gamow's *The Birth and Death of the Sun*, published in 1940, this book is a lively introduction to the physics of our parent star and guardian angel. Now and then Gamow is a little high, wide and handsome about theories and even facts, but by and large this is an excellent brand of popularization—sound teaching, good reading, filled with delights and curiosities. Illustrations.

Notes

PRINCIPLES OF MATHEMATICS, by Bertrand Russell. W. W. Norton & Company, Inc. ($2.95). A soft-cover reprint of Russell's famous book devoted to the thesis that mathematics and logic are the same subject.

THE FEYNMAN LECTURES ON PHYSICS: VOLUME II, by Richard P. Feynman, Robert B. Leighton and Matthew Sands. Addison-Wesley Publishing Company, Inc. ($8.75). The second volume of these lectures, the first volume of which was noted in these columns some months ago, deals with the electromagnetic field.

ELECTRONS, ATOMS, METALS AND ALLOYS, by William Hume-Rothery. Dover Publications, Inc. ($2.25). A revised third edition in paperback of Hume-Rothery's introduction to the application of electron theory to the structure and properties of metals and alloys, the presentation cast in an unusual but nevertheless agreeable and helpful form: a dialogue between "Old Metallurgist" and "Young Scientist."

AFRICAN ECOLOGY AND HUMAN EVOLUTION, edited by F. Clark Howell and François Bourlière. Aldine Publishing Company ($12.50). Papers and discussion transcriptions of a symposium sponsored by the Wenner-Gren Foundation for Anthropological Research, held in Austria in 1961, dealing with such topics as Pleistocene stratigraphy and climatic changes in Africa, the origin and evolution of the earliest manlike creatures there, the ecology, biology and social behavior of African primates and human populations.

NATIONAL PHYSICAL LABORATORY REPORT FOR 1963. Her Majesty's Station-

ery Office ($3.40). Reports on the year's activities by the various divisions of Britain's National Physical Laboratory, among them aerodynamics, basic and applied physics, autonomics, mathematics, metallurgy and standards.

GENERALIZED FUNCTIONS, by I. M. Gel'fand and G. E. Shilov. Academic Press ($12). The first of five volumes of a mathematical treatise dealing with generalized functions, including many of their applications to various problems of analysis, translated from the Russian by Eugene Saletan.

POISONOUS PLANTS OF THE UNITED STATES AND CANADA, by John M. Kingsbury. Prentice-Hall, Inc. ($13). A survey of literature on poisonous plants and the toxicology of plant poisoning in men and animals.

LIFE HISTORIES OF NORTH AMERICAN GALLINACEOUS BIRDS and LIFE HISTORIES OF NORTH AMERICAN GULLS AND TERNS, by Arthur Cleveland Bent. Dover Publications, Inc. ($2.75 each). Softcover editions of two of the volumes in Bent's noted series on North American birds, published under the auspices of the Smithsonian Institution between three and four decades ago.

BIOCHEMISTRY OF INDUSTRIAL MICROORGANISMS, edited by C. Rainbow and A. H. Rose. Academic Press ($22). A cooperative survey that covers older processes, such as the fermentation industries, the production of baker's yeast, enzymes, organic acids and vitamins, and also recent developments in the making of alkaloids, amino acids, antibiotics, gibberellins and steroids.

A DICTIONARY OF BIOLOGICAL TERMS, by I. F. Henderson and W. D. Henderson. D. Van Nostrand Company, Inc. ($12.50). The revised eighth edition of this work defines more than 16,000 terms in biology.

GENETICS TODAY, edited by S. J. Geerts. Pergamon Press ($15). Abstracts of contributed papers, demonstrations and films presented at the Eleventh International Congress of Genetics, held at The Hague in 1963.

ADVANCES IN MARINE BIOLOGY, edited by F. S. Russell. Academic Press ($13.50). A new serial publication containing review articles intended to help biologists to keep abreast of knowledge in research on the biology of marine organisms.

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

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