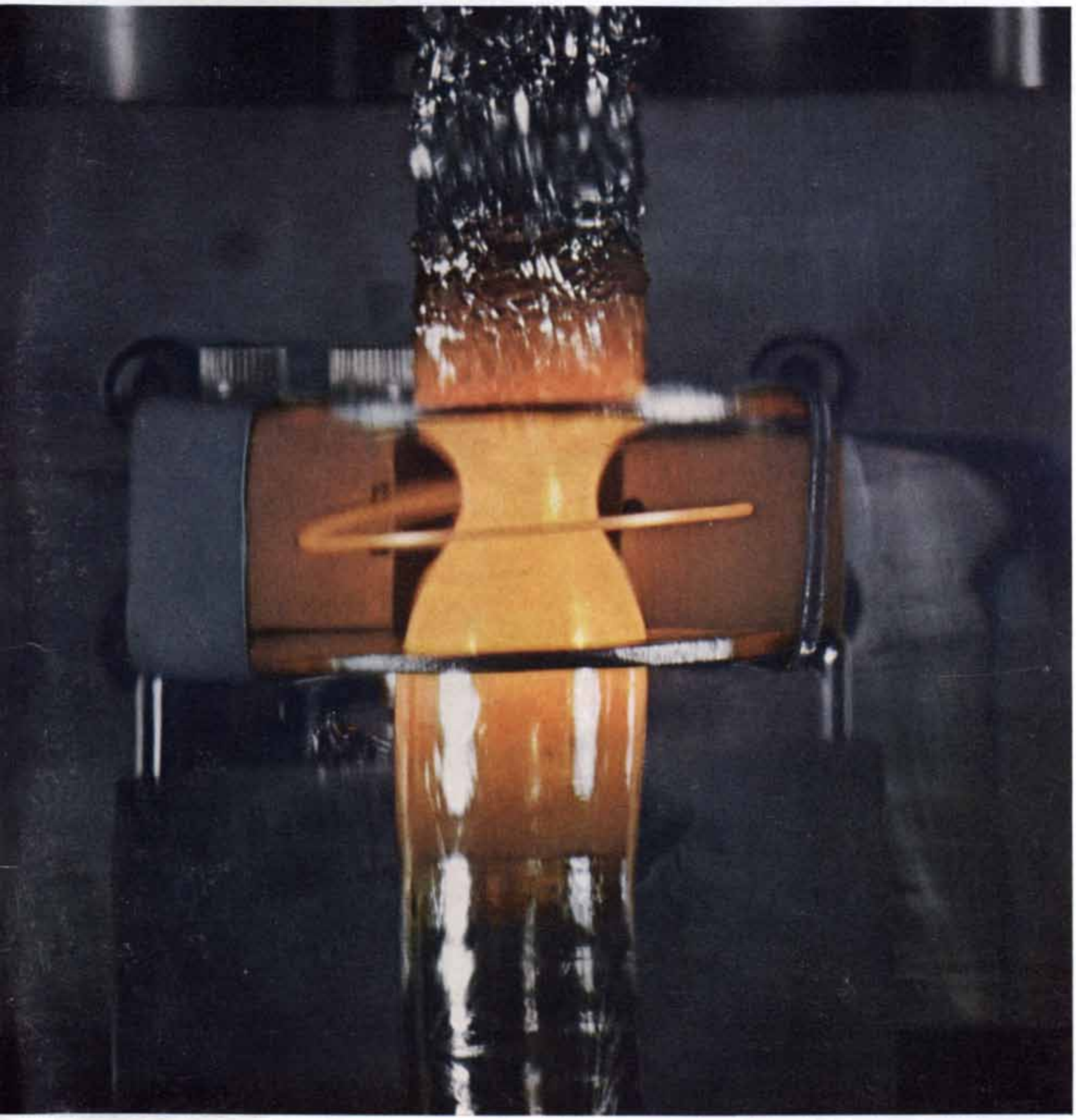
SCIENTIFIC AMERICAN



ZONE REFINING

SEVENTY-FIVE CENTS

December 1967

Eastern opens The Space Corridor.

Along it lie 4 key centers of aerospace activity.

Boeing in Seattle. McDonnell in St. Louis. The George C. Marshall Space Flight Center in Huntsville. And Cape Kennedy.

Now Eastern links them all in one direct route. With daily round-trip jet service from Seattle to Orlando and Melbourne.

The Space Corridor means new convenience for the traveler. As well as a new kind of service.

The kind of service that has made Eastern the choice of one in six of the nation's air passengers.

A reservation confirmed in seconds.

A leisurely meal with your choice of gourmet entrées. Expertly prepared.

And a competence of flight and maintenance personnel second to none.

Because we offer more than a shortcut to space. We make it more enjoyable getting there.

EASTERN

We want everyone to fly.

Now, a videotape recorder that goes anywhere you go.

He's taping that thrilling number, "Serenade in Peep Major" with the new portable, battery-operated Sony Videocorder.

It records both picture and sound. (The camera weighs only 6 pounds. The recorder pack just 12.) Needs only you to operate it. And costs only $1250.* Yet it can do just about everything one of those gargantuan mobile video units can do. Maybe even more.

It doesn't have yards of power cable to tie it down. (One thin cable connects the Camera and Recorder. That's all.) So it can go up in a plane and tape aerial views of potential factory sites. Tag along on an archaeological expedition. Or on a trip to the zoo with a bunch of first graders. Or it can even wiggle into tight places and crawl beneath machinery to record damage. (So only one person has to get his clothes dirty.)

Anyone can operate this Sony Videocorder. All its level controls are fully automatic. And there's a TV monitor right inside the camera. So it's almost impossible to botch things up. (If you manage to do it anyway, no sweat. The tape is reusable.)

The nicest thing about the Videocorder: when you come back with everything behind you, it instantly lets you have it all in front of you.

SONY® PORTABLE VIDEOCORDER®

*Manufacturer's suggested retail price—including battery charger and zoom lens.

This tank grows over two inches every time it's emptied. The only trouble was, its outer skin didn't grow with it.

The challenge was to find a material that would.

A tank that stores liquid anhydrous ammonia at –28° F. must be heavily insulated from the outside. And that insulation must be securely protected with a weather barrier that will hold up. An ordinary barrier system might have done the job but in this case there was one demanding requirement: when the warm tank was filled with liquid ammonia, it shrank; and when it was emptied, it expanded, up to 2.3" in circumference.

Teamed up with a major fiber producer, WestPoint Pepperell had already engineered the solution: Wellnel, a reinforcing fabric engineered with high elongation fiber to withstand expansions and contractions of the largest tanks and pipes. The result: a 90 per cent saving in weather barrier maintenance expense.

Putting fabrics to work in applications like this is our specialty at WestPoint Pepperell Industrial Fabrics Division, where engineering fabrics for industry is our full-time business.

If you have a problem, any problem, that fabric could solve, why don't you get in touch with us now. In any case, your files on materials of design are incomplete unless you have our booklet: "Engineered Fabrics for Industry." Write to 111 West 40th Street, New York, N.Y. 10018.

WestPoint Pepperell™

INDUSTRIAL FABRICS DIVISION

(FORMERLY WELLINGTON SEARS)

Established 1845 **SCIENTIFIC AMERICAN** December 1967 Volume 217 Number 6

ARTICLES

DEPARTMENTS

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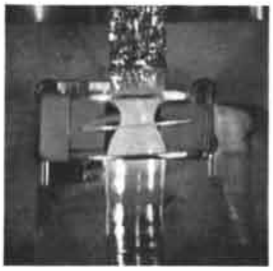

THE COVER

The photograph on the cover shows a multicrystalline ingot of titanium (*top*) being converted to a single crystal of exceptionally high purity (*bottom*) by the process known as float-zone refining (see "Zone Refining," page 62). The titanium, held only at the top and bottom, is raised slowly through a circumferential wire that acts as a cathode and sends out a stream of electrons to melt the ingot, which acts as the anode in the circuit. The bright yellow molten zone is held in place simply by surface tension. As the "floating" zone passes upward through the ingot it picks up impurities and sweeps them along to the upper end of the ingot. The process is usually repeated several times to produce a crystal of desired purity. The picture was made at the Materials Research Corporation in Orangeburg, N.Y.

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Cover photograph by Sol Mednick

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LOOK WHO'S DRIVING A ROLLS-ROYCE

World's fastest corporate aircraft—the new Grumman Gulfstream II powered by Rolls-Royce fan-jets.

In 1958 Grumman Aircraft revolutionized corporate travel with Gulfstream I—a fast, comfortable, reliable plane that was powered by Rolls-Royce prop-jets. Now Grumman is ready with a successor—Gulfstream II. Its powerful Rolls-Royce fan-jets will make cross-country business trips as matter-of-fact as the commuter's special.

Ask a busy executive for his version of the perfect corporate aircraft. It will undoubtedly have the speed and range of a commercial airliner. The economy and ease of handling of a small, private plane. And be able to carry 15 to 20 people.

Grumman's own Gulfstream I met most of these requirements at speeds up to 355 mph. Planes that could go faster than this lacked in other ways. They had limited range and could carry only a handful of passengers.

A big engine for a small plane

Then the breakthrough came. Rolls-Royce started building a new fan-jet engine called the Spey. The Spey developed surprising power for its size—at first glance, perhaps more power than was actually needed for a purely corporate aircraft. But that suited Grumman just fine. From the outset, they intended Gulfstream II to outperform other corporate planes. And they made full use of the Spey's extra power to do it.

New York to L.A. in 5 hours

First off, they used it to carry a full load—up to 19 passengers, a crew of three and almost two tons of interior furnishings.

Second, they used it for fast takeoff. The extra power gets Gulfstream II into the air quickly. It can use local airports.

Third, they used it for fast climb. Gulfstream II takes just 15 minutes to get up to 40,000 feet, far above the weather.

Fourth, they used it for range. Gulfstream II can fly non-stop from coast to coast. New York to Los Angeles, for example, in just 5 hours—with 90 mph headwinds all the way.

And last but not least, they used it for speed. Gulfstream II can cruise at 585 mph—making it the fastest corporate jet in the world.

So far, 70 orders have been placed for Gulfstream II, even though deliveries have just begun.

In good company

Grumman Aircraft is not the only manufacturer to put the Spey to work. It powers the BAC One-Eleven used by American, Braniff, Mohawk and Aloha Airlines. It substantially improves the performance of the McDonnell Douglas F-4 Phantom ordered by the British Government for the Royal Navy and Royal Air Force. Versions of the Spey also power the Hawker Siddeley Trident, the Fokker F-28, the U.S. Air Force's new A-7D and the Royal Navy's Hawker Siddeley Buccaneer.

All in all, the Spey powers more different aircraft than any other fan-jet engine. The Grumman Gulfstream II couldn't be in better company.

Look who else is driving a Rolls-Royce

Most people think of the Rolls-Royce Silver Shadow as the ultimate motor car.

But did you know that Rolls-Royce also builds the diesel engine that powers this heavy-duty excavator?

That Rolls-Royce industrial engines generate electricity, pump gas, power hydrofoils and run chemical processing plants?

That Rolls-Royce reactor cores power all of Britain's nuclear submarines?

That Rolls-Royce builds multifuel engines that run equally well on gasoline, kerosene, jet fuel or diesel fuel?

Rolls-Royce. One of the world's great engine builders.

ROLLS RR ROYCE

Rolls-Royce Limited, Derby England
(Incorporating Bristol Siddeley Engines Limited.)
Sales representative: 551 Fifth Avenue, New York, N.Y. 10017

LETTERS

Sirs:

In her article on the researches of Robert Boyle [SCIENTIFIC AMERICAN, August] Marie Boas Hall did not mention one aspect of his work that is of interest in view of the attention now taken in the science of materials. In his book *Experiments and Considerations about the Porosity of Bodies* (London, 1684) Boyle published pioneering observations on solid-state reactions and drew attention to the phenomenon of "a solid and heavy body soaking into the pores of a metal," in modern words, to solid-state diffusion in metals.

A large part of the book is devoted to an essay, "Porousness of Solid Bodies," in which Boyle describes experiments on solid-state reactions, including the tarnishing of silver in sulfur fumes and the reaction of copper plates heated in contact with sulfur and arsenic.

Perhaps even more interesting is his experiment of diffusing a substance, which he does not identify "because of the bad use that can be made of it," into a copper coin. This rendered the coin golden. It seems likely, however, that the substance was zinc, known to him as speltrum, and that he had prepared the copper-zinc alloy later used as imitation gold under the name of Pinchbeck....

Throughout the book Boyle constantly refers to the porosity of solids by which such phenomena are to be explained. This concept seems closely related to the modern idea of vacant lattice sites and voids in solids. His speculation that density measurements might detect such porosity has been confirmed in recent years.

L. W. BARR

Harwell, England

Sirs:

In the light of William P. Lowry's article "The Climate of Cities" in your August issue, it is interesting to consider some remarks contained in a book published in 1841 by the American meteorologist James Pollard Espy. In his book *The Philosophy of Storms* Espy included a letter he had sent to the *National Gazette* in 1839, in which he said: "If the principle is correct, that clouds are formed by upmoving columns of air, we should expect to find, in favorable states of the air, that clouds would form over large cities and manufacturing towns where much fuel is burnt, and so we find it to be."

Espy further quotes the following from Edward Mammatt's *Collection of Facts Concerning Ashby Coal Field,* published in London in 1836: " 'When the air is apparently stagnant in the valley of the Thames and surrounding country, a strong current is found to set in, on every side of London, along the streets leading from the country, in the morning. This current is no doubt occasioned by the rarefaction in the high chimneys over so many thousand fires just kindled, and must be the cause of the introduction of fresh air to an immense extent, which would not otherwise flow. This rarefaction produces other phenomena, among which, when the atmosphere is in a light state, and clouds are passing at a height which does not allow them to condense and fall in rain, these accumulate in passing over London, and either remain as a dense fog, or drop in small rain all day long, scarcely clearing once; the country, at a little distance, having very little rain.' "

In spite of some misconceptions and errors, these observations are remarkably good for the time, yet they seem to have received little attention.

JAMES W. CERNY

Portsmouth, N.H.

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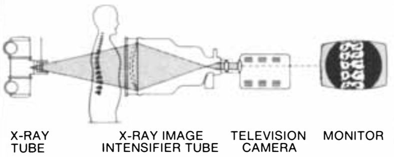
TV special in X-ray room B

This radiologist, using a TV monitor, is viewing an X-ray image of Jimmy's heart 5,000 times brighter than that displayed by a standard fluoroscopic screen. What makes the difference? An X-ray image intensifier tube that is lifting fluoroscopy out of the dark ages and lighting the way for doctors to use revolutionary new techniques.

Today, heart specialists can accurately position cardiac catheters within the heart chamber to pinpoint defects and provide precise diagnosis. Using a similar technique, other specialists can examine in detail the function of the kidneys and other vital organs. Orthopedic surgeons can actually see fractures being set. Even routine procedures, such as gastro-intestinal examinations, are improved by the radiologist's ability to see a brighter image.

FIGURE I — TYPICAL SYSTEM USING TV MONITOR



The red goggles are gone

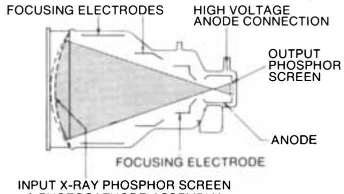
As recently as eight years ago, a radiologist preparing to fluoroscope a patient donned red goggles at least twenty minutes in advance of the examination to adapt his eyes to the darkened fluoroscopic room. Even then, his vision was so limited that images on the fluoroscopic screen appeared dim and hazy. Thus, he was unable to make full use of the inherent potential of fluoroscopy.

Now, using an X-ray image intensifier tube, the radiologist views a bright, clear image displayed on a TV monitor (or other optical display) in a normally-lighted room (Fig. 1). Not only can he see more, but he now has a wide choice of readout methods. He can record the examination on motion picture film or video tape for later consultation or review. And, for training and remote, instantaneous consultation, he can feed the display to other locations via closed circuit TV.

How an X-ray image intensifier works

X-rays emerging from the patient's body pass through the input end of the tube (Fig. 2) and strike a glass plate coated on one side with an X-ray sensitive, zinc-cadmium-sulfide phosphor.

FIGURE 2 — SCHEMATIC DIAGRAM OF X-RAY IMAGE INTENSIFIER TUBE



These rays, attenuated in varying degrees by the portion of the body they have just penetrated, cause the phosphor to fluoresce in a pattern identical to that of the penetrated structure. Light from the fluorescing phosphor then strikes a photocathode layer on the opposite side of the glass plate causing it to emit electrons in a similar pattern. These electrons are accelerated and focused on a small phosphor screen at the output end of the tube. The output screen converts the electron beam into a small light image which is 5,000 times brighter than the original X-ray image on the input screen.

This phenomenal gain in brightness is accomplished in three separate ways: First, the photocathode is a highly efficient converter of light energy. Second, the energy of the electrons from the photocathode is increased by the application of high voltage to the anode. And, finally, reduction of the image greatly increases the brightness.

These image intensifier tubes are produced by Machlett Laboratories, a Raytheon subsidiary and the world's largest manufacturer of X-ray tubes. The same basic technology is being applied to enable our soldiers to see in the dark and may someday find widespread use in industry and in everyday life.

This is typical of how Raytheon is finding better ways to serve people and the nation . . . in space and defense systems, and in such commercial areas as natural resources exploration, education, home appliances, components, marine electronics and communications. Raytheon Company, Lexington, Massachusetts.

RAYTHEON

50 AND 100 YEARS AGO

Scientific American

December, 1917: "As an effective weapon of war it seems that the tank has a brilliant future, not only when its construction will have been considerably improved upon but especially when tank tactics are developed to a fine point as a result of considerable experience with them. French tanks played an important role in the last battle of the Chemin des Dames, when the Germans were swept off the Aisne heights and into the valley beyond. More recently, the British tanks distinguished themselves in the battle of Cambrai, at the head of General Byng's infantry, which swept forward without the usual artillery preparation. We are told that the tanks maneuvered about in squad formation and were entirely successful in tearing down great stretches of the enemy's barbed wire entanglements and in smashing his concrete shelters and dispersing his machine gunners. Considerably over 100 tanks were employed, according to reports."

"It is announced from Mount Wilson that a new star of about the 14th magnitude has appeared in the spiral nebula N.G.C. 6946. In connection with this discovery, Dr. H. D. Curtis points out that this is the sixth time the appearance of a nova has been reported in a spiral nebula. The number of these cases indicates that the new stars in question were actually in the nebula, and not merely in a line with it as seen from our system."

"A unique observation made independently by two English observers, Messrs. Ainslie and Knight, has been reported to the British Astronomical Association. On Feb. 9, 1917, a seventh-magnitude star was seen to pass behind the outer ring of Saturn into the Cassini division (the space between the outer and middle rings), and after grazing the second ring and moving for some time along the Cassini division, to traverse again the outer ring, and finally emerge from its outer edge. In other words, the star was occulted by a part of Saturn's ring system. The interesting feature of the observation is that the star was plainly visible at all times while behind the ring, though its brightness was diminished to about one-fourth. This fact indicates that the particles composing the ring must be of quite small size."

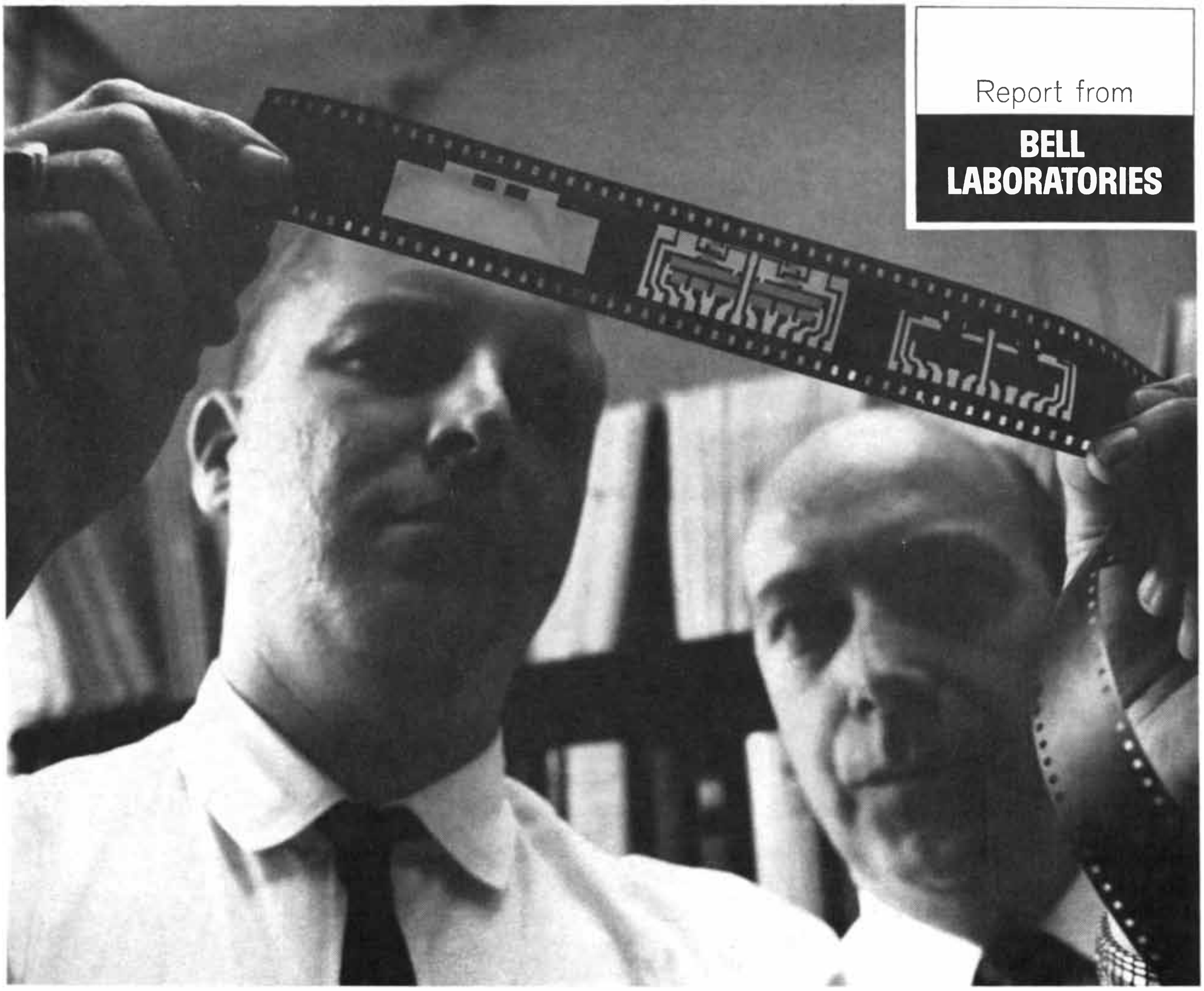
"The town of Rocky Mount, N.C., has set a good example to other Southern communities by establishing a school for midwives and requiring them to pass a satisfactory examination before receiving permits to practice their occupation. Instruction is free and is given by the city health officer. Although the school was recently started, a falling off in the infant death rate is already noted. In North Carolina almost twice as many Negro babies as white die during their first week, owing largely to the fact that ignorant midwives are so generally employed by the Negroes in place of physicians."

"During the week ending April 21st, 1917, when the submarine crisis was at its height, the German U-boats sank 40 merchant ships of over 1,600 tons and 15 of less than 1,600 tons—a total of 55 ships. During the week ending November 11th, 1917, they sank one ship of over 1,600 tons and five below 1,600 tons—a total of six ships."

Scientific American

December, 1867: "The number of Bessemer steel converters now established in Europe totals 115, which are capable of producing half a million of tuns per annum. England with 52 converters turns out weekly 6,000 tuns. Prussia with 22 converters is the next greatest producer, 1,460 weekly. Next comes France with 12 converters and 880 tuns; Austria, 14 converters and 650 tuns; Sweden, 15 converters and 530 tuns. The Bessemer process is worked at one locality only in Belgium, and Italy has two establishments, with a very small yield."

"Five hundred twenty-five miles of the Union Pacific Railroad running west from Omaha across the continent are now completed. This brings the line to the eastern base of the Rocky Mountains, and it is expected that the track will be laid 30 miles farther to Evans Pass, the highest point on the road, by January. The maximum grade from the foot of the mountains to the summit is but 80 feet to the mile, while that of many eastern roads is over 100. Work in the rock cut-



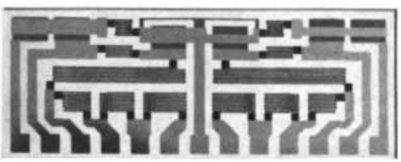
Report from
BELL LABORATORIES

Thin films: faster by computer

Arthur G. Gross and Harry M. Kalish of Bell Telephone Laboratories have developed a computer program whose end product is a set of correctly sized photographic "masks" for making prototype thin-film networks. The masks control the deposition and shapes of various widths and thicknesses of conductive, resistive, and dielectric materials that make up such circuits. (These frequently begin as tantalum, deposited onto a glass or ceramic substrate and chemically treated to produce desired electrical properties.)

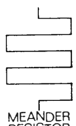
Controlled by the new program, a computer feeds a precision microfilm plotter which prints the masks on 35mm film (photo above).

With this system, a prototype can be ready in a day, as against the weeks that may be involved in making high-precision masks for volume circuit production. Usually, for example, a draftsman must make rough sketches and prepare a list of numbers (coordinate points) accurately describing the geometry of the final circuit. Then the actual shapes—greatly enlarged—are cut into plastic sheets on a "coordinatograph." Later, the plastic patterns are photographically reduced to circuit-sized masks, perhaps ½ by 1 inch.



An experimental thin-film filter network—in actual size—made from 35mm film masks. In the top photo, A. G. Gross (left) and H. M. Kalish hold three of the masks used. Each mask controls the formation of a layer of conductive, resistive, or dielectric material. The circuit is built up of a number of such layers.

In addition to reducing time and handling, Bell Laboratories' new program relieves the engineer of another tedious job: designing the meandering lines that constitute resistors in these circuits. And the computer resistors are "optimized" . . . fitted into the smallest possible area.



MEANDER RESISTOR

To give the engineer freedom to use irregular plane shapes, the program includes a subroutine which closely approximates geometric figures used in making thin-film circuits.

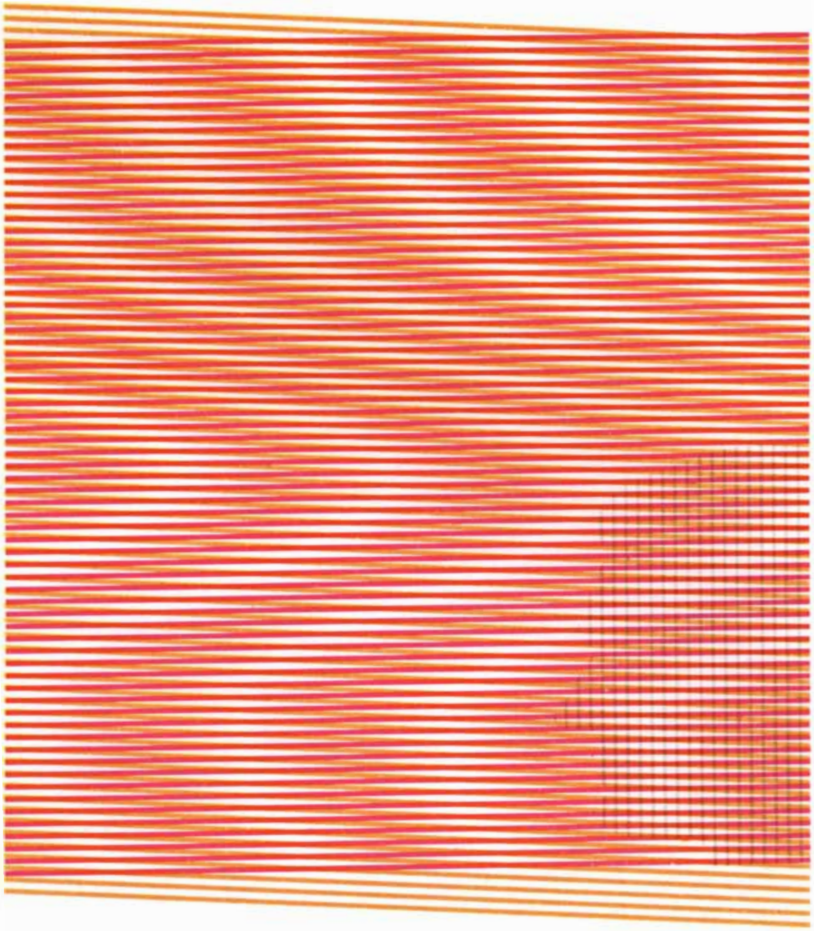
Bell Telephone Laboratories
Research and Development Unit of the Bell System

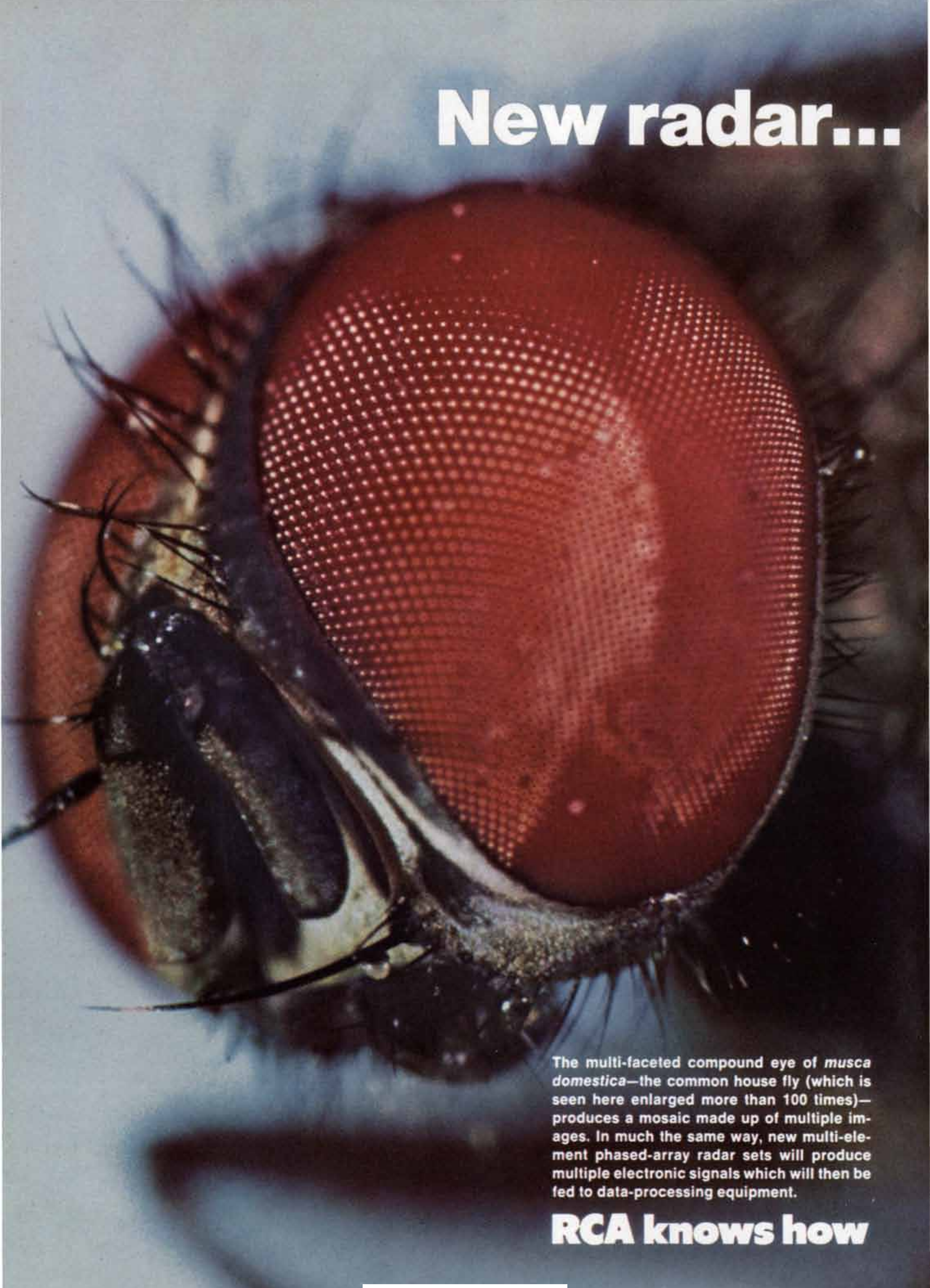
tings on the western slope will continue through the winter, and there is now no reason to doubt that the entire grand line to the Pacific will be open for business in 1870."

"A gigantic suspension bridge has been designed by M. Oudry, engineer, to span the Straits of Messina between Sicily and the Calabrian coast of Italy. It is to consist of four spans of 3,281 feet each, elevated about 150 feet above high-water level, so that the largest ships may pass under it. The proposed Roebling bridge over the East River between New York and Brooklyn is to have a single span of 1,600 feet."

"M. Krupp is about to construct at his works at Essen a single-acting steam hammer far exceeding in size any now in existence. The design for this hammer—which will have a head weighing 120 tuns—has already been prepared, and the patterns are now in hand. At present the largest hammer at M. Krupp's enormous establishment is one with a 50-tun head."

"Some time ago the death of a young lady passenger, Miss Stainsby, in one of the cars of the London underground railway was reported caused, as then alleged, by suffocation due to the bad state of the air in the tunnels. A legal investigation ensued from which it now appears that one of the causes of her death was tight lacing. Prof. Rodgers, lecturer on medical jurisprudence and on chemistry, was the first witness, and at his request the evidence of Dr. Popham as to the appearance of the body was read to him. Dr. Popham added that he had found the deceased was tightly laced, and that the result would be to compress her chest and impede the free action of her lungs. Prof. Rodgers said he had examined samples of air taken on four different occasions from the tunnels of the Metropolitan Railway, and also from various other tunnels. The slight deficiency of oxygen which he found would not act injuriously, even upon delicate persons, passing as they did rapidly through the tunnel in trains. He thought that under the circumstances under which the deceased had entered the train—that was to say, considering that she had eaten heartily, was tightly laced, had a diseased heart and was already faint before she entered the tunnel—her death had resulted from natural causes. The jury heard other evidence and then, without hesitation, brought in a verdict:—'Died from natural causes.' "




New radar...
The multi-faceted compound eye of musca domestica—the common house fly (which is seen here enlarged more than 100 times)—produces a mosaic made up of multiple images. In much the same way, new multi-element phased-array radar sets will produce multiple electronic signals which will then be fed to data-processing equipment.
RCA knows how

"sees" like a fly

Soon you may be protected by a new type of radar—uninhibited by the need for mechanical methods. The primary advantage of this phased-array radar system is its near-instantaneous ability

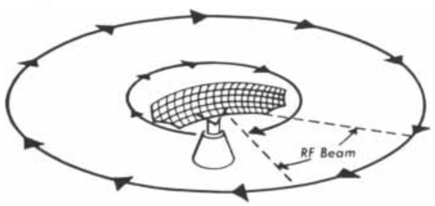


Fig. 1

to "look" from one direction to another like the fly. This advanced system can function effectively and conveniently, with relatively low power requirements and at reduced over-all cost in contrast to present-day radar.

Today, even when two or more conventional sets are operated together for reinforcement to cover a greater area, each separate set can still only report the presence of objects in one relatively small segment at a time. It must search—as shown in *Fig. 1*—by successive sweeps of individual antennas through relatively small and slow changes of azimuth and vertical deflection. Such multiple-set systems have limited capability because of their sheer bulk, which increases as additional scanning units are added, and their need for large mechanically-steered antennas.

With systems using the new type radar, both near-instantaneous omnidirectional scanning and simultaneous tracking of multiple targets are practicable for the first time *electronically.* To make this possible, engineers at RCA Electronic Components and Devices are reducing the size and improving the performance of each part of the radar system—shown in simplified block diagram in *Fig. 2.* One way this is now being done is by the use of transistor-driven harmonic generator chains as the transmitter's power source. In the receiver (that handles RF echoes), RCA engineers are also accomplishing size reduction and performance improvement by using an integrated low-noise tunnel-diode amplifier.

Further size reduction and improved performance of present radar components is promised by the creation of complete microwave circuits which, like the aforementioned receiver, use RCA's advanced methods for vapor deposition of metals in thin layers on tiny ceramic substrates. *Fig. 3* points up the small size of one such vapor-deposited complete microwave circuit now being developed by RCA for a military application. Similar reductions in component size will soon enable RCA to build boxes—only inches on a side—which will contain all of the discrete electronic elements of a radar system.

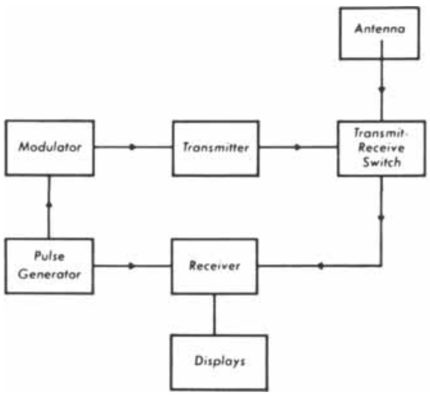


Fig. 2

This, in turn, will lead radar manufacturers—including RCA—to new design concepts which will use multiple small antennas, each with its own miniaturized transmitter and receiver. Arrays of antenna and system modules such as these will be controlled by a computer, and give radar the fastest scan capabilities yet conceived. By controlling—or phasing—the operation of such units electronically, they can be made steerable in both azimuth and vertical deflection *without moving parts.* Although the radio frequency power output of each individual unit will be relatively low, the effective radiated power (ERP) of the entire system will be high when many units are phased to be mutually supporting. High ERP—producing greater range, more sensitivity and freedom from noise—will allow radar designers to improve systems performance.

RCA engineers eventually will displace discrete elements of radar systems with bulk-effect devices using such materials as gallium arsenide. These bulk-effect devices, each conceivably smaller than the head of a pin, could be operated in combination to generate megawatts of pulsed microwave power for improved range and target discrimination.

Taking these bulk-effect devices from the laboratory into full-scale production calls for RCA's skills...learned in the batch production of currently-available solid-state devices. Day by day, these techniques result in improved performance and lower-cost-per-unit of transistors, monolithic integrated circuits and switching devices. Foreseeable as one end-result of RCA technology will be wholly-new, low-cost electronically-steerable phased-array radar systems...weather units for aircraft; units for military applications; radar for shipboard and land-based use—both fixed and mobile.

It is already possible for radar manufacturers to plan for such systems, with 100, 1,000 or more individual antennas. Each will be equipped with its own transmitter-receiver package, and all will be steered electronically.

Radar systems—without moving

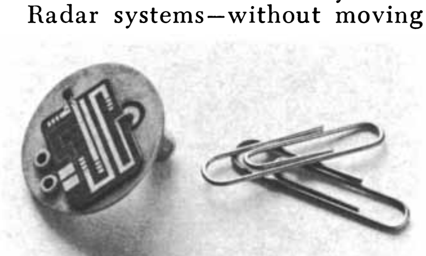


Fig. 3

parts—will have real-time capability to "see" like the fly.

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ELWYN L. SIMONS ("The Earliest Apes") is professor of paleontology at Yale University and curator in charge of vertebrate paleontology at Yale's Peabody Museum of Natural History. He holds a B.A. from Rice University, a Ph.D. from Princeton University and a D.Phil. from the University of Oxford. Since joining the Yale faculty in 1960 Simons has led 10 expeditions in search of primate and other vertebrate fossils—four to Wyoming and six to Egypt. An expedition to northern India in search of the earliest relative of man, *Ramapithecus,* begins this winter.

RICCARDO GIACCONI ("X-Ray Stars") heads the Space Research and Systems Division of American Science and Engineering, Inc. A native of Italy, Giacconi received a doctorate in physics from the University of Milan in 1954. He taught at Milan until 1956, when he came to the U.S. as a Fulbright Fellow to do research at Indiana University on the interactions of high-energy cosmic ray particles. In 1958 and 1959 he was at Princeton University, where he was associated with the development of a plastic-fiber scintillation chamber for detecting elementary particles. In 1959 he joined American Science and Engineering, where he established a one-man department in the field of space research, an initial effort that has now grown to a 200-man division. In 1966 he was awarded the Helen B. Warner Prize of the American Astronomical Society for his discovery of X-ray sources outside the solar system and for his invention, with Bruno Rossi of the Massachusetts Institute of Technology, of an X-ray telescope. Giacconi is currently directing the work for the Project Apollo X-ray-telescope experiment. He also has the responsibility of principal investigator in a project to design, construct and fly the scientific payload for the X-ray Explorer satellite, scheduled to be launched in 1970.

WILLIAM G. PFANN ("Zone Refining") is head of the department of crystal growth and zone-melting research in the metallurgical research laboratory of the Bell Telephone Laboratories. Pfann has been associated with Bell Laboratories since 1935, when he began work as a messenger boy. He attended evening classes in chemical engineering at the Cooper Union School of Engineering, obtaining a B.Ch.E. in 1940. Since then he has worked on microscopy, point-contact diodes for radar receivers, erosion of electrical contacts, semiconductive devices and processes, zone melting, dislocation phenomena and crystal growth. He holds more than 50 U.S. patents and is the author of a comprehensive book, *Zone Melting.* In 1962 he was an Overseas Fellow at Churchill College of the University of Cambridge. He has received many honors and awards, and he is to be the first recipient of the recently created Award for Creative Invention of the American Chemical Society.

VERNON D. BARGER and DAVID B. CLINE ("High-Energy Scattering") are associate professors of physics at the University of Wisconsin. Barger was educated at Pennsylvania State University, where he obtained a Ph.D. in theoretical physics in 1963. Cline did his undergraduate work at Kansas State University, acquiring a Ph.D. from Wisconsin in 1965. For the past two years Barger and Cline have collaborated on studies of strong interactions at high energy. They remark: "Our collaboration revolves primarily around the explanation of new experimental data. The collaboration is well balanced, with theoretical calculations handled by Barger and experimental aspects by Cline."

E. EUGENE HELM ("The Vibrating String of the Pythagoreans") is associate professor of music at the University of Iowa. A graduate of Southeastern Louisiana College, Louisiana State University and North Texas University (where he received a Ph.D. in musicology), Helm writes: "My interest in resounding strings undoubtedly goes back to my undergraduate days, when I was a misguided physics major. I remember that I was the only student in sophomore physics lab who, during our search for loops and nodes, could make the piece of paper jump off the string of the monochord at the very first pluck. Being a misguided violinist at the time, I knew perfectly well where the loops were."

PAUL J. COHEN and REUBEN HERSH ("Non-Cantorian Set Theory") are professors of mathematics at Stanford University and the University of New Mexico respectively. Cohen attended Brooklyn College, acquired a Ph.D. frcm the University of Chicago in 1958 and has taught at the University of Rochester, the Massachusetts Institute of Technology and Harvard University. He is currently visiting at the Institute for Advanced Study in Princeton. Largely for the work described in this article, he was awarded the Fields Medal at the 1966 International Mathematical Congress. He was also a co-winner of the Research Corporation of America's annual $10,000 award for research by an American scientist. In 1963 he won the Bôcher prize, awarded annually by the American Mathematical Society for outstanding research in analysis. Hersh has taught at New York University, Fairleigh Dickinson University and Stanford. He reports that before taking his Ph.D. in mathematics from N.Y.U. in 1962 he had earned a B.A., magna cum laude, in English literature at Harvard, served in the U.S. Army of Occupation in Korea, spent four years as an office boy and editorial assistant with SCIENTIFIC AMERICAN and four years in the machine-building trade as engine-lathe hand and experimental machinist.

W. ROSS COCKRILL ("The Water Buffalo") is employed by the Food and Agriculture Organization of the United Nations and is stationed at the FAO headquarters in Rome. A 1935 graduate of the Royal College of Veterinary Surgeons, Cockrill worked for a time in general practice in his native country of Scotland, did research and as a government veterinary officer engaged in the control of bovine tuberculosis, foot-and-mouth disease and other diseases of economic importance to the livestock industry. He became a Fellow of the Royal College of Veterinary Surgeons in 1950 and is also a doctor of veterinary medicine at the University of Zurich. During World War II he served with the Royal Air Force as a flying officer. Since joining the FAO he has traveled widely and during the past 15 years has visited and worked in some 60 countries.

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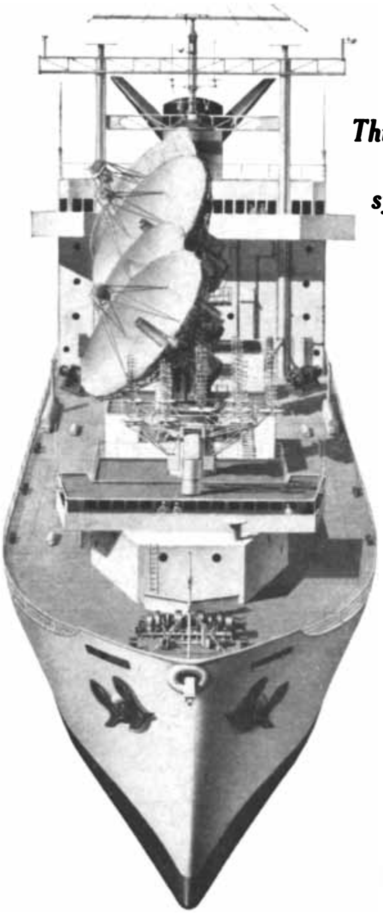

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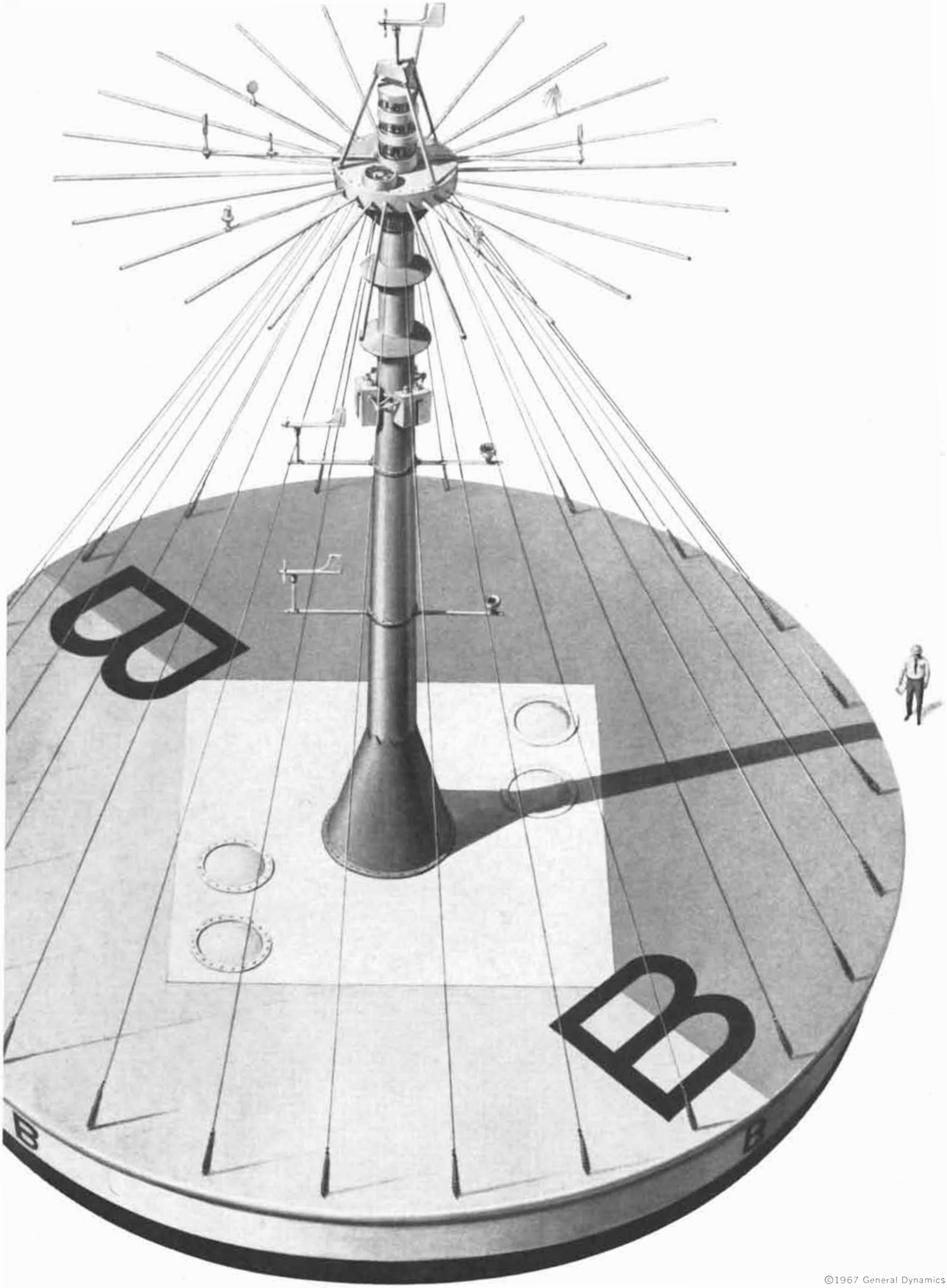

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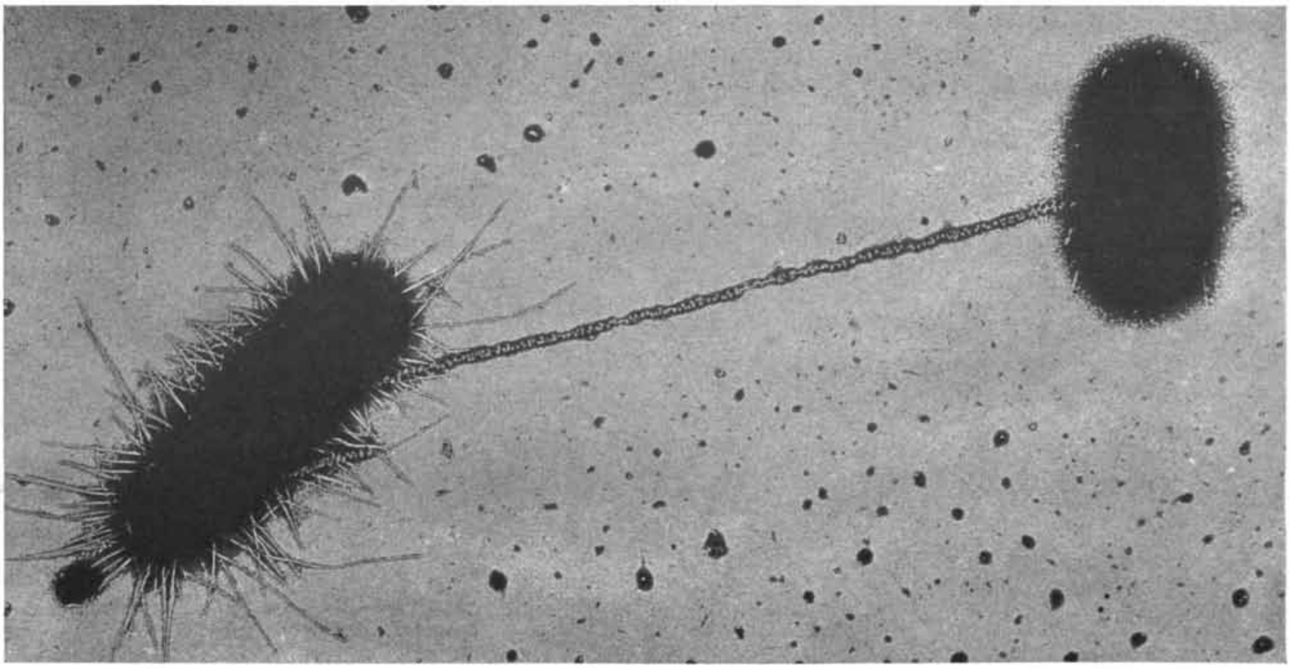
Infectious Drug Resistance

Bacteria can suddenly become resistant to several antibacterial drugs. The resistance is transferred from one strain to another by an "episome" that carries the genes for multiple resistance

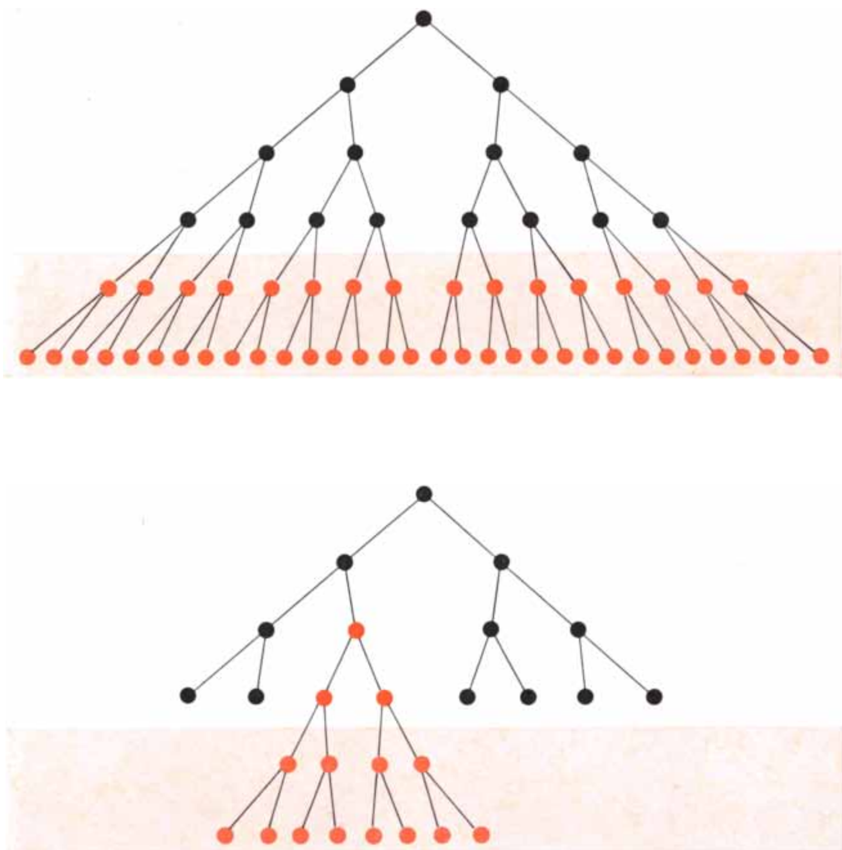
by Tsutomu Watanabe

The advent of sulfonamide drugs and antibiotics brought with it the promise that bacterial disease might be brought under control, but that promise has not been fulfilled. Although many infections respond dramatically to chemotherapy, tuberculosis, dysentery and typhoid fever continue to be endemic in many parts of the world; cholera and plague erupt periodically; staphylococcal infections persist in the most advanced medical centers. One major reason is that the disease organisms have developed resistance to the drugs.

Until recently it was assumed that the appearance of drug-resistant bacteria was the result of a predictable process: the spontaneous mutation of a bacterium to drug resistance and the selective multiplication of the resistant strain in the presence of the drug. In actuality a more



R FACTOR, the particle that imparts infectious drug resistance, is transferred from one bacterial cell to another by conjugation. The various forms of conjugation are thought to be effected by way of thin tubules called pili. In this electron micrograph made by Charles C. Brinton, Jr., and Judith Carnahan of the University of Pittsburgh a male *Escherichia coli* cell (*left*) is connected to a female bacterium of the same species by an *F* pilus, which shows as a thin white line in the negatively stained preparation. Numerous spherical bacterial viruses, or phages, adhere to the *F* pilus. The cells have been magnified about 20,000 diameters.



DRUG RESISTANCE involves a change in the genetic material of a bacterial cell. The change from drug-sensitive cell (*black*) to drug-resistant cell (*color*) is not induced by the presence of the drug (*light color*), as was once thought (*top*). It is the result of a spontaneous mutation that gives rise to cells that survive in the drug environment (*bottom*).

ominous phenomenon is at work. It is called infectious drug resistance, and it is a process whereby the genetic determinants of resistance to a number of drugs are transferred together and at one stroke from a resistant bacterial strain to a bacterial strain, of the same species or a different species, that was previously drug-sensitive, or susceptible to the drug's effect. Infectious drug resistance constitutes a serious threat to public health. Since its discovery in Japan in 1959 it has been detected in many countries. It affects a number of bacteria, including organisms responsible for dysentery, urinary infections, typhoid fever, cholera and plague, and each year it is found to confer resistance to more antibacterial agents. (What may be a related form of transmissible drug resistance has been discovered in staphylococci and may be responsible for "hospital staph" infections.) Quite aside from its importance to medicine, the study of infectious drug resistance is making significant contributions to microbial genetics by illuminating the complex and little understood relations among viruses, genes and the particles called episomes that lie somewhere between them.

If an antibacterial drug is added to a liquid culture of bacteria that are sensitive to the drug, after a while all the cells in the culture are found to be resistant to the drug. Once it was thought that the drug must somehow have induced the resistance. What has actually happened, of course, is that a few cells in the original culture were already resistant; these cells survive and their daughter cells multiply when the sensitive majority of bacteria succumb to the drug [*see illustration above*]. The resistance was not induced by the drug but was the result of a spontaneous mutation. Bacteria, like higher organisms, have chromosomes incorporating the genetic material, and from time to time a gene—perhaps one controlling drug resistance—undergoes a mutation. The mutation of a drug-sensitivity gene occurs only once in 10 million to a billion cell divisions, and when it occurs it alters a cell's sensitivity to one particular drug or perhaps two related drugs.

In 1955 a Japanese woman recently returned from Hong Kong came down with a stubborn case of dysentery. When the causative agent was isolated, it turned out to be a typical dysentery bacillus of the genus *Shigella*. This shigella was unusual, however. It was resistant to four drugs: sulfanilamide and the antibiotics streptomycin, chloramphenicol and tetracycline. In the next few years the incidence of multiply drug-resistant shigellae in Japan increased, and there were a number of epidemics of intractable dysentery.

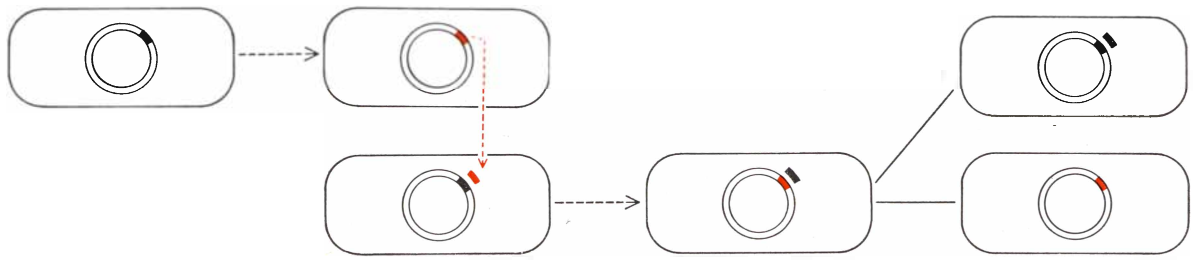
The familiar process of mutation and selection could not explain either this rapid increase in multiple resistance or a number of other findings concerning the dysentery epidemics. For one thing, during a single outbreak of the disease resistant shigellae were isolated from some patients and sensitive shigellae of exactly the same type from other patients. Even the same patient might yield both sensitive and resistant bacteria of the same type. Moreover, the administration of a single drug, say chloramphenicol, to patients harboring a sensitive organism could cause them to excrete bacteria that were resistant to all four drugs. Then it was found that many of the patients who harbored drug-resistant shigellae also harbored strains of the relatively harmless colon bacillus *Escherichia coli* that were resistant to the four drugs. It was impossible, on the other hand, to obtain multiple resistance in the laboratory by exposing sensitive shigellae or *E. coli* to any single drug; multiply resistant mutants could be obtained only after serial selections with each drug in turn, and these mutants, unlike the ones taken from sick patients, multiplied very slowly.

Taken together, these characteristics of the resistant shigellae suggested to Tomoichiro Akiba of Tokyo University in 1959 that resistance to the four drugs might be transferred from multiply resistant *E. coli* to sensitive shigellae within a patient's digestive tract. Akiba's group and a group headed by Kunitaro Ochiai of the Nagoya City Higashi Hospital thereupon confirmed the possibility by transferring resistance from resistant *E. coli* to sensitive shigellae—and from resistant shigellae to sensitive *E. coli*—in liquid cultures. Other investigators demonstrated the same kind of transfer in laboratory animals and eventually in human volunteers. Clearly a new kind of transferable drug resistance had been discovered. What, then, was the mechanism of transfer? There were three known mechanisms of genetic transmission in bacteria that had to be considered as possibilities.

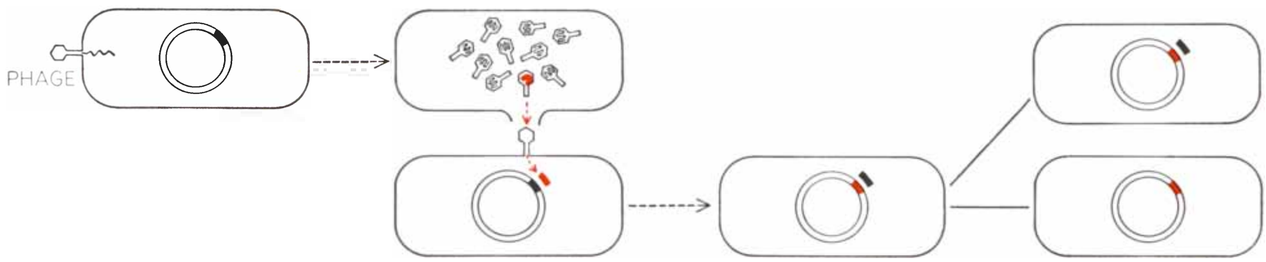
One was transformation, which involves "naked" deoxyribonucleic acid (DNA), the stuff of genes. DNA can be extracted from a donor strain of bacteria and added to a culture of a recipient strain; some of the extracted genes may "recombine," or replace homologous genes on chromosomes of the recipient bacteria, thus transferring a mutation from the donor to the recipient [*see top illustration below*]. In this way, for example, streptomycin-sensitive bacteria can become streptomycin-resistant.

Transformation occurs in a number of different bacteria, and it can occur spontaneously as well as experimentally. Because only small fragments of DNA are taken up by bacteria in transformation, however, it is seldom that more than two different drug-resistance genes are transferred together. It requires optimal laboratory conditions, moreover, for transformation to occur at a significant frequency, and such conditions are not likely to prevail in nature.

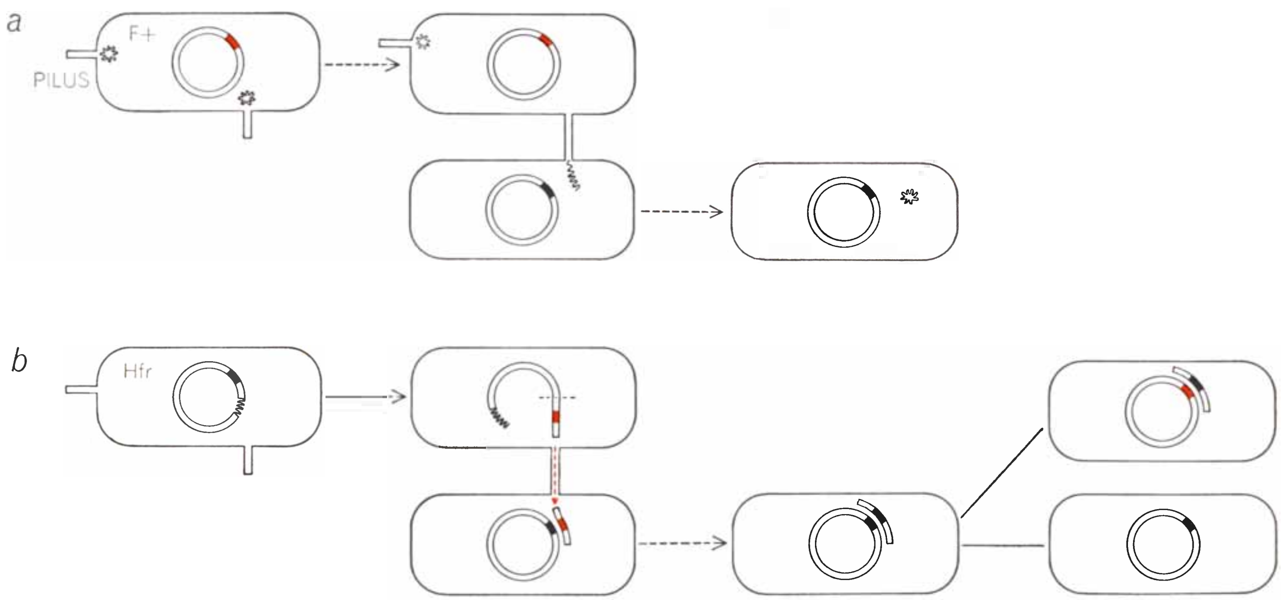
Another mechanism of gene transmission is transduction, in which genes are



TRANSFORMATION is a form of genetic transmission in which deoxyribonucleic acid (DNA) extracted or excreted from a donor cell (*top*) enters a recipient cell (*bottom*) and is incorporated into its chromosome. In this way a mutated gene (*color*) controlling resistance to a drug may be transferred to a drug-sensitive cell, replacing a homologous gene, which is unable to replicate and dies out.



TRANSDUCTION is effected by phage, or bacterial virus. Phage DNA enters a cell (*left*) and directs the synthesis of new phage, killing the cell (*second from left*). A bit of bacterial DNA (*color*), perhaps a mutated gene that causes drug resistance, may be incorporated inside a newly formed phage, be carried to a sensitive cell (*bottom*) and "recombine," or replace a gene on the chromosome.



SEXUAL MATING is a form of conjugation. If a fertility factor (F) is in the cytoplasm of a male (F^+) cell (*a*), it is transferred alone through a pilus to a female (F^-) cell. In an *Hfr* cell (*b*) the *F* is incorporated in the chromosome. Cell-to-cell contact causes part or all of the chromosome, perhaps including a mutation for drug resistance (*color*), to pass to a female cell and recombine.

carried from one bacterial cell to another by infecting phages, or bacterial viruses. Transduction occurs when a phage, reproducing inside a cell by taking over the cell's synthesizing machinery, incorporates a bit of the bacterial chromosome within its protein coat "by mistake." When the phage subsequently infects a second cell, the bacterial genes it carries may recombine with homologous genes on the second cell's chromosome. The phage in effect acts as a syringe to bring about what in transformation is accomplished by the movement of naked DNA [*see middle illustration on preceding page*]. Transduction takes place in a variety of bacteria, but at a very low frequency. Genes for resistance can be transduced like other genes, but it is unlikely that more than two resistance genes could be transferred together because the small transducing phage can carry only a short segment of bacterial chromosome.

The third type of genetic transmission in bacteria is conjugation: a direct contact between two cells during which genetic material passes from one cell to the other. Transfer by conjugation occurs primarily from male to female cells of certain groups of bacteria. The male bacteria carry a fertility factor, the *F* factor, that is ordinarily located in the cytoplasm of the cell but may become integrated into the chromosome. When the *F* is cytoplasmic, the male cells are called F^+. In such cells the *F* is readily transferred to female (F^-) cells by conjugation, but it is transferred alone. When the *F* factor is integrated into the bacterial chromosome, it serves to "mobilize" the chromosome. That is, the chromosome, which in bacteria forms a closed loop, opens and portions of it can pass by conjugation to a female cell, recombine with the female chromosome and thereby endow the female bacterium with traits from the male. Because this transfer occurs with a high frequency in male cells with an integrated *F*, such cells are called *Hfr*, for "high frequency of recombination" [*see bottom illustration on preceding page*].

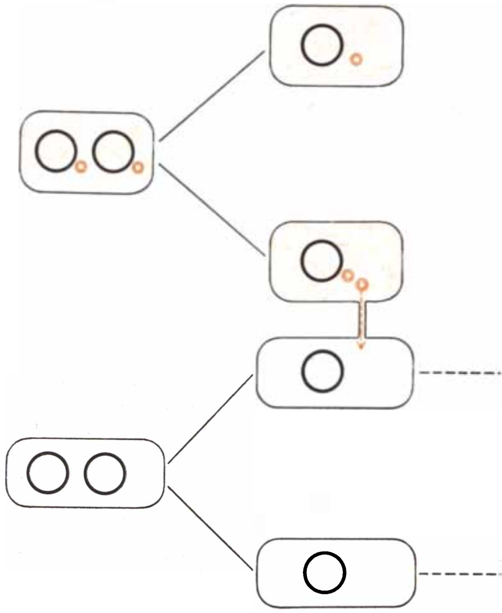
The *F* factor is what is generally called an episome: a genetic element that may or may not be present in a cell, that when present may exist autonomously in the cytoplasm or may be incorporated into the chromosome, and that is neither essential to the cell nor damaging to it. An episome is something like a virus without a coat; indeed, some bacterial viruses can become "temperate" and exist as harmless episomes inside certain bacterial cells [see "Viruses and Genes," by François Jacob and Elie L. Wollman; SCIENTIFIC AMERICAN, June, 1961].

Until recently the actual route of transfer was not known. In 1964 Charles C. Brinton, Jr., of the University of Pittsburgh and his colleagues proposed that the *F* factor or the *F*-mobilized chromosome passes from one cell to the other through a thin tubular appendage, the *F* pilus, that is formed on both F^+ and *Hfr* cells by the presence of the *F* factor. Another kind of pilus, the Type 1 pilus, is seen on female cells as well as male cells, but the two can be distinguished: the *F* pilus is the site of infection by certain phages, and so the phages cluster along the *F* pili, marking them clearly in electron micrographs [*see top and middle illustrations on page 25*].

If a male chromosome transferred to a female cell by conjugation carries drug-resistance genes, these genes may be incorporated into the female chromosome. Experiments with sexual mating showed that drug-resistance genes are in fact sometimes scattered along bacterial chromosomes. Rather long segments—sometimes the entire length—of the chromosome can be transferred in sexual mating, and so it is possible for several resistance genes to be transferred in a single mating event.

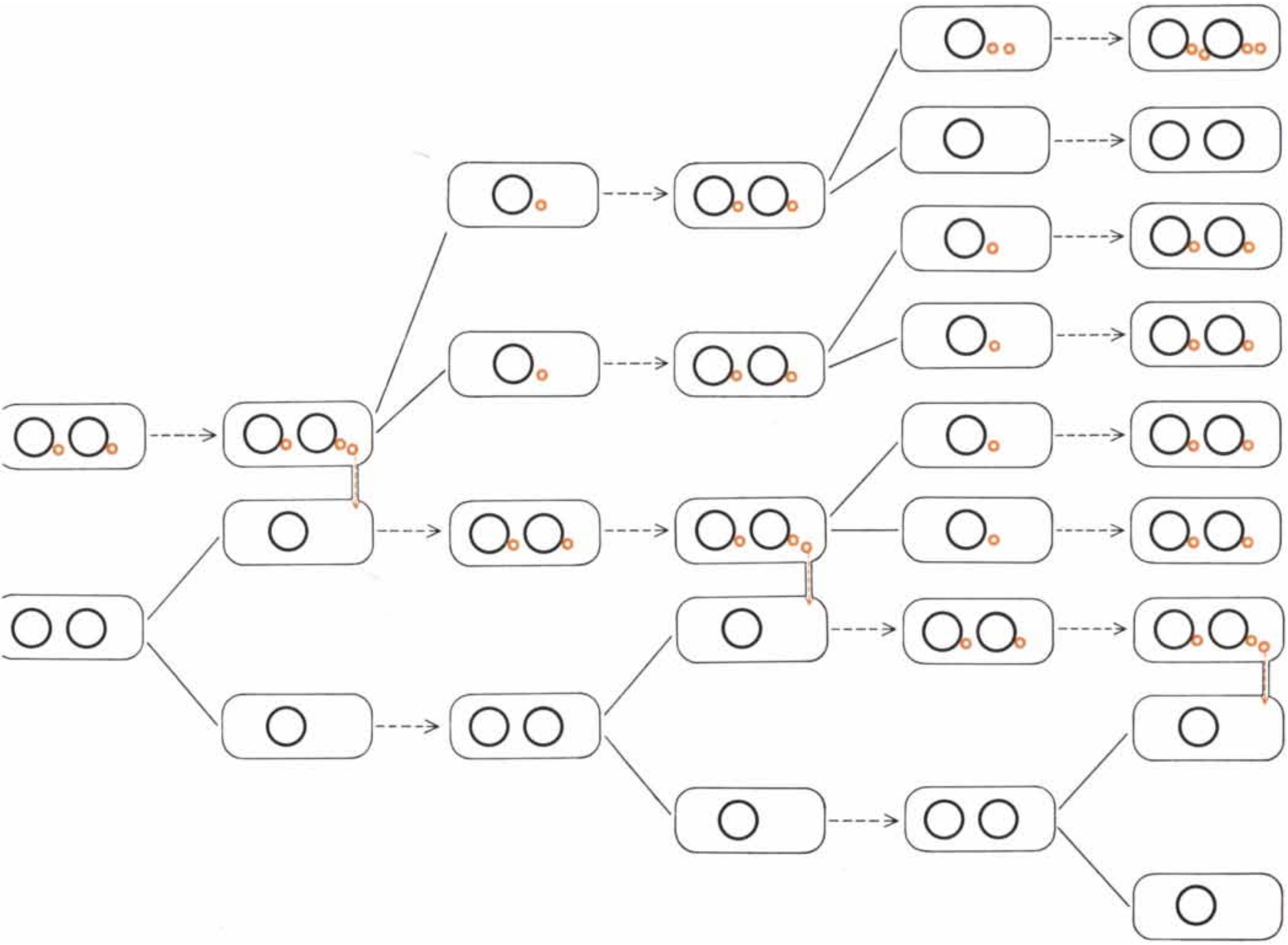
In 1960 we took up the study of the resistant shigellae in my laboratory at the Keio University School of Medicine. It soon became clear that the mechanism of transfer of multiple resistance was not transformation, because sensitive strains were not made resistant by DNA extracted from the resistant bacteria. It was not transduction, because it could not ordinarily be effected by cell-free filtrates of the resistant cultures.

There was strong evidence that some form of conjugation must be responsible. Microscopic examination of a mixed culture of sensitive and resistant bacteria revealed pairing between the different kinds of cells. When a mixed liquid culture was agitated in a blender to break off any cell-to-cell contact, and the culture was then diluted to prevent further pairing, the transfer of resistance ceased. If the mechanism of resistance transfer was conjugation, however, it was not the familiar process of sexual mating. For one thing, it occurred between F^- cells. Moreover, two observations showed that unlike the transmission of traits by sexual mating the transfer did not involve the chromosome itself. First, we noted that known chromosomal traits of certain strains, such as the inability to synthesize particular substances, were not usually transferred along with the drug-resistance traits. Second, we noted that the recipient cells became resistant immediately after the transfer occurred, whereas chromosomal drug resistance is ordinarily expressed only after the original drug-sensitivity genes have been lost in the course of cell division through the process known as segregation.



INFECTIOUS DRUG RESISTANCE, another form of conjugation, involves transfer of the *R* (resistance) factor. A cell of a re-

We concluded that the factor responsible for infectious drug resistance was an extrachromosomal element, which we called the *R* factor (for "resistance"). A number of experiments have confirmed the cytoplasmic nature of these factors. They are obtained by bacteria only by infection from other *R*-factor-carrying cells, never by spontaneous mutation. They can be eliminated from cells by treatment with acridine dyes; *F* factors can be eliminated in the same way when they are in the cytoplasm of F^+ cells but not when they are incorporated into the



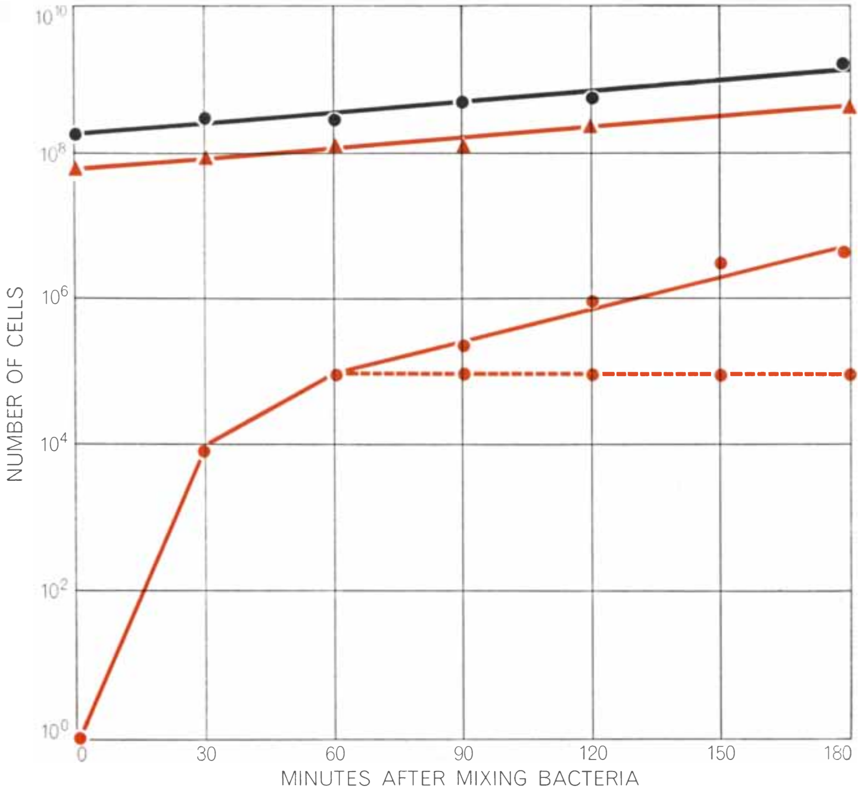
sistant strain (*light color*) comes in contact with one of a sensitive strain (*white*); one of its *R* factors (*color*) replicates and a copy passes through a pilus to the sensitive recipient. The procedure is repeated as cells come in contact. In the course of cell division an *R* factor is sometimes lost. The diagram is highly schematic; the actual sequence of replication and transfer is not established.

chromosome of *Hfr* cells. Finally, consider what happens when one adds a small number of bacteria with *R* factor to a culture of drug-sensitive cells. There is a rapid increase in the relative number of drug-resistant cells; in 24 hours or so the culture is almost completely resistant. This must be owing to the rapid infectious spread of *R* factors to the once sensitive bacteria, because it occurs at a much faster rate than the overall growth of the culture [*see top illustration on next page*]. Since chromosome replication is synchronized with cell division, the *R* factor must be replicating faster than the chromosomes and must therefore replicate outside the chromosome, in the cytoplasm.

Although the *R* factor is usually located in the cytoplasm, in rare instances it is integrated into the chromosome, and when that happens it is transferred together with some chromosomal genes. Such behavior suggests that the *R* factor, like the *F* factor, is episomal in nature. Both of them may be of selective advantage to the cells in which they exist, the *F* factor by making for genetic variability and the *R* factor of course by providing drug resistance. When they are not providing an advantage, they at least do the host cells no harm; they are symbionts rather than harmful parasites. Their behavior is similar to that of a temperate, or nonvirulent, phage, and it may be that both are descended from bacterial viruses. Unlike viruses, they cannot exist at all outside the cell; they are obligatory intracellular symbionts with even less biological function than viruses, which are usually considered to be on the borderline between living and nonliving matter.

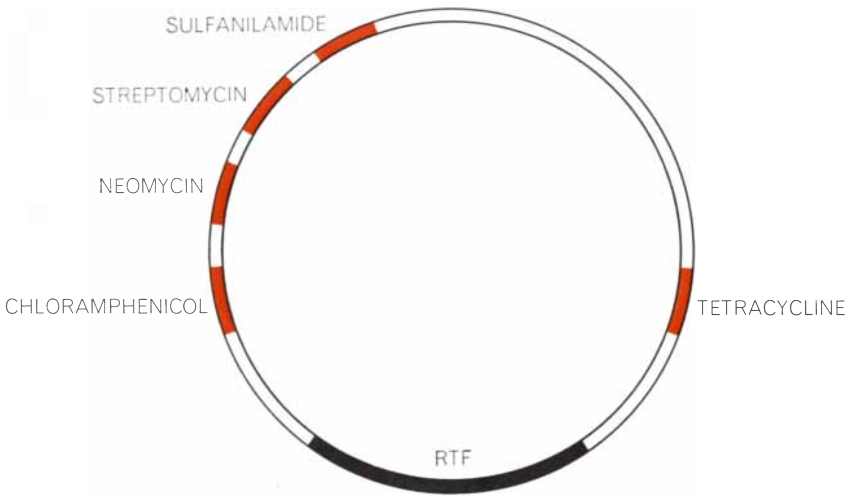
There is a further major point of similarity between the *F* and the *R* factor, and that is their method of transfer. In London, Naomi Datta of the Royal Postgraduate Medical School, A. M. Lawn of the Lister Institute of Preventive Medicine and Elinor Meynell of the Medical Research Council observed in 1965 that most *R* factors induce the formation of pili that are shaped like *F* pili and attract the same phages as *F* pili: apparently they *are F* pili [*see bottom illustration on page 25*]. When bacteria that have such pili and are able to transmit multiple resistance are severely agitated in a blender, the pili are sheared off. Such "shaved" cells are unable to transfer the *R* factor; later, when the *F* pili have been regenerated, the cells are once again infectious. It now appears that both *R* factors and any chromosomal genes mobilized by *R* factors are transferred by the *F* pili or another closely related kind of pili.

The big difference between the transfer of *F* factors and the transfer of *R* factors is in the frequency with which they occur. In a mixed culture of male



TIME COURSE of *R*-factor transfer is shown. Equal volumes of cells of a donor *E. coli* strain infected with *R* factors (*triangles*) and of an initially sensitive recipient strain (*black dots*) were mixed. Sampling at intervals traced the increase in the number of resistant *E. coli* (*colored dots*). After one hour some of the culture was removed, agitated to break off cell-to-cell contact and diluted to prevent pairing. In the diluted culture there was no increase in the number of resistant cells (*broken line*), indicating that conjugation was the mechanism of transfer. The data are from David H. Smith of the Harvard Medical School.

and female bacteria the transfer of nearly 100 percent of the *F* factors or *F*-mobilized chromosome, as the case may be, occurs within an hour. In a culture of drug-resistant (donor) and drug-sensitive (recipient) bacteria, on the other hand, only 1 percent or less of the donor cells transfer their *R* factors in an hour. The low frequency of transfer is due to the relative scarcity of cells with *F* pili in a culture of bacteria carrying *R* factors. Bacteria that have newly acquired the *R* factor, on the other hand, can transfer it at a very high frequency—almost 100 percent. (If this were not the case, *R* factors could hardly multiply so rapidly in a newly infected culture.) They lose this high competence after several cell-division cycles. The explanation seems to be that most *R* factors form a "repressor" substance that somehow inhibits the formation of *F* pili. Cells that are newly infected with such *R* factors contain no repressor, and so *F* pili are initially induced at a high frequency. Later, as the repressor accumulates, the formation of the pili is inhibited.



MAP OF *R* FACTOR, still tentative, shows a closed loop. There are five determinants (*color*) of resistance to five different drugs. There is also a determinant, the resistance-transfer factor (*black*), that controls the ability of the *R* factor to replicate and be transferred.

It is now possible to describe what happens when bacteria with the *R* factor come into contact with a population of drug-sensitive bacteria [*see illustration on preceding two pages*]. A few *R* factors are transmitted by conjugation from donor cells bearing pili into the cytoplasm of recipient cells, which immediately become resistant. The transfer process is repeated from cell to cell, and the normal process of cell division also contributes to the rapid proliferation of multiple resistance in the recipient population. From time to time an *R* factor is lost. Both the rate of transfer and the rate of loss vary in different strains of bacteria and *R* factors, thus accounting in part for the fact that naturally occurring multiple resistance is much more common in some bacteria that are susceptible to infectious drug resistance than in others.

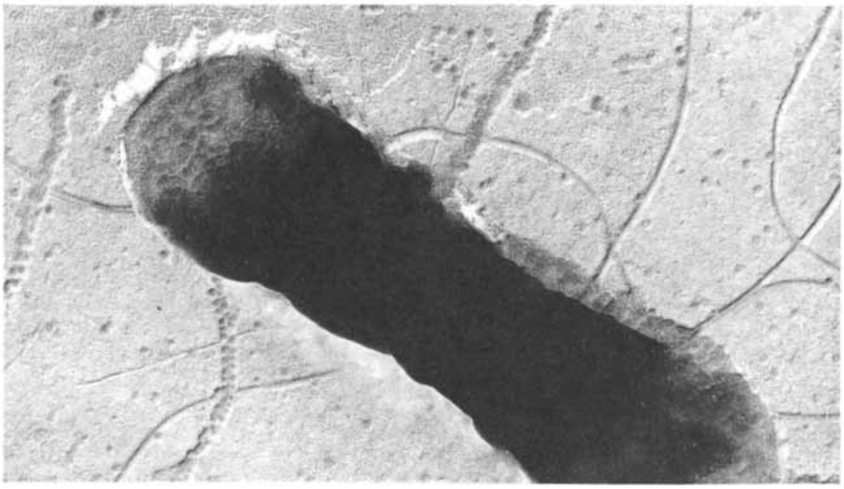
For several years we have been seeking to map the various elements of an *R* factor as one maps the genes of a chromosome. To do this we capitalize on the fact that although *R* factors are not normally transferred by transduction, it is possible to transduce them under carefully controlled conditions. If we grow large phages in a culture of bacteria with *R* factors, a few of the phages pick up entire *R* factors and are capable of transferring them to recipient cells. If we use small phages, there is room for only part of the *R* factor to be incorporated inside their protein coats and transduced. Some of the transduced particles impart drug resistance but lack the ability to replicate or to be transferred by conjugation; others lack determinants of one or more of the multiple drug resistances. By calculating the frequency with which various segments of the *R* factor are transduced together, we can determine their relative distance from one another and so visualize the structure of the *R* factor we are studying.

The map is not yet conclusive, but we think the factor is circular and that it has a segment—the resistance-transfer factor, or RTF—that controls replication and transferability, as well as segments determining resistance to each of five types of drug [*see bottom illustration on opposite page*]. We have suggested that the *R* factors originate when a resistance-transfer factor picks up resistance genes from some bacterial chromosome and that the two then form a single episomal unit. E. S. Anderson and M. J. Lewis of the Central Public Health Laboratory in London have advanced a different view. They consider that the resistance-transfer factor and the set of resistance determinants exist as two separate units, which on occasion become associated to form *R* factors.

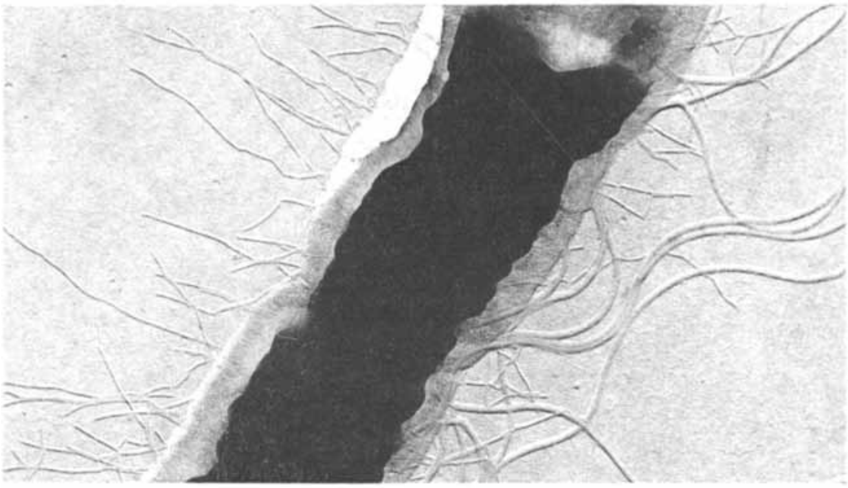
Since *R* factors are self-replicating units, carry genetic information and can recombine with bacterial chromosomes, it is safe to assume that they are composed of DNA. This is confirmed by the fact that *R* factors, like nucleic acids in general, are inactivated by ultraviolet radiation and by the decay of incorporated radioactive phosphorus. At the Walter Reed Army Institute of Research and at Keio, Stanley Falkow, R. V. Citarella, J. A. Wohlhieter and I were able to isolate the DNA of *R* factors by density-gradient centrifugation. A first attempt to separate *R*-factor DNA from that of *E. coli* was unsuccessful, suggesting that the densities of the two DNA's are very similar. We then selected as the host cell the bacterium *Proteus mirabilis*, which was known to have a DNA of unusually low density and to be subject to infectious drug resistance.

When DNA extracted from *Proteus* carrying the *R* factor is centrifuged in a solution of cesium chloride, two satellite bands of DNA appear in addition to the band characteristic of the bacterial DNA [*see illustration on next page*]. These bands disappear if the *Proteus* loses its *R* factors spontaneously or if they are eliminated by the acridine dye treatment, and so we conclude that the bands do represent the *R*-factor DNA. Analysis of this fraction by column chromatography shows that it is typical double-strand DNA. It is possible that *R* factors contain components other than DNA, but this is not likely in view of the fact that entire factors are transduced and transducing phages incorporate only DNA.

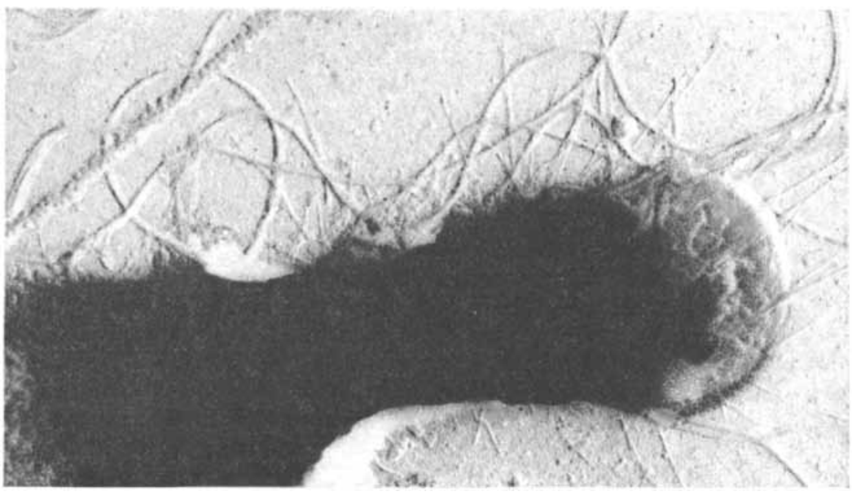
The original finding that infectious drug resistance affected four unrelated drugs implied that some factor was altering the cell membrane, reducing its permeability and thereby barring all the drugs from their normal sites of action inside the cell. The finding that there are separate resistance determinants for the various drugs, however, indicated that



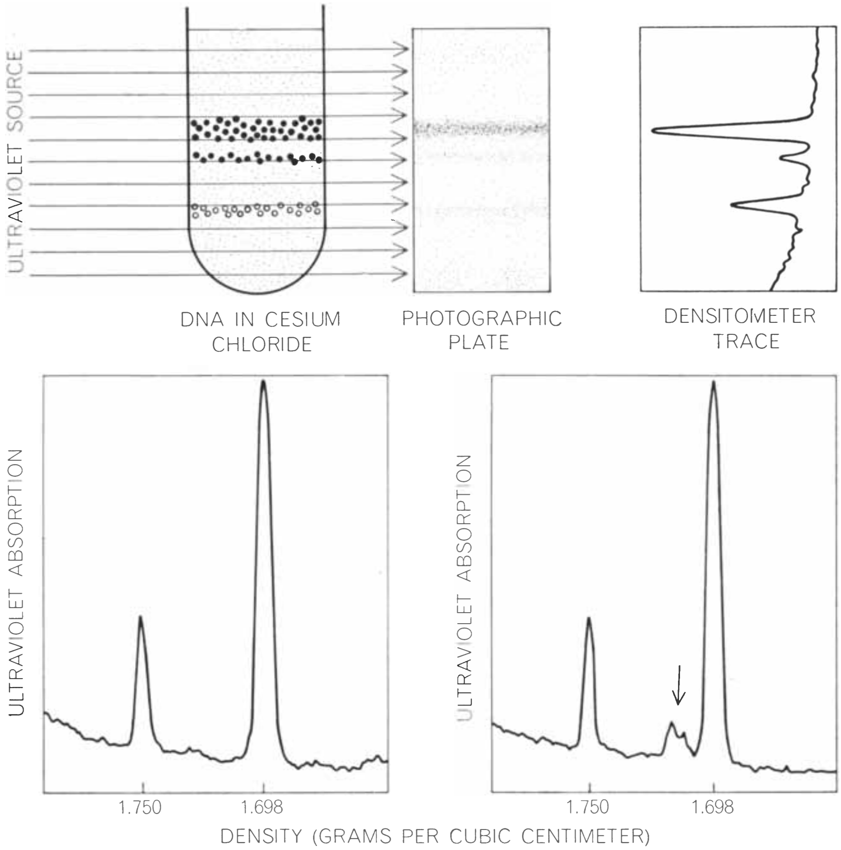
MALE BACTERIUM, an *E. coli* infected with phage, has *F* pili. They are thin fibers, here hidden below the spherical phage particles. The thin fibers without phages are Type 1 pili and the thick fibers are flagella. The preparation has been enlarged about 30,000 diameters.



FEMALE *E. COLI*, which lacks the *F* factor, also lacks *F* pili. It does have both the Type 1 pili and flagella, which are organelles of locomotion for the cell. The electron micrograph, like the others on this page, was made by Toshihiko Arai in the author's laboratory.



***E. COLI* WITH *R* FACTOR, although a female cell, does carry an *F* pilus, the phage-covered fiber at top left. It also has Type 1 pili and flagella. The most common type of *R* factor initially induces the formation of *F* pili, but it also tends to repress them later.**



R-FACTOR DNA is isolated by density-gradient centrifugation. DNA from *Proteus* cells is suspended in a cesium chloride solution and spun in a high-speed centrifuge. The cesium chloride establishes a density gradient and the DNA forms bands in the solution according to its density. The DNA pattern is photographed in ultraviolet, which is absorbed by DNA, and the photograph is scanned by a densitometer (*top*). The densitometer trace derived from *Proteus* without *R* factor (*bottom left*) shows a band at 1.698 grams per cubic centimeter that is characteristic of *Proteus* DNA and a reference band at 1.750. The trace from *Proteus* with *R* factor (*right*) has extra bands (*arrow*) at 1.710 and 1.716, representing *R*-factor DNA.

each determinant had its own mode of action. Permeability may be involved in the case of some drugs, but it is now clear that other processes are at work. S. Okamoto and Y. Suzuki of the National Institute of Health in Japan and Mrs. Datta and P. Kontomichalou in Britain have shown that bacteria bearing various *R* factors synthesize particular enzymes that inactivate specific drugs, thereby rendering them harmless to the bacteria.

The public health threat posed by infectious drug resistance is measured by the range of bacterial hosts it affects, the number of drugs to which it imparts resistance and the prevalence of certain practices in medicine, agriculture and food processing that tend to favor its spread. *R* factors can be transferred not only to shigellae but also to *Salmonella,* one species of which causes typhoid fever; to *Vibrio cholerae,* the agent of cholera; to the plague bacillus *Pasteurella pestis* and to *Pseudomonas aeruginosa,* which causes chronic purulent infections. In addition, more than 90 percent of the agents of urinary tract infections, including *E. coli, Klebsiella, Citrobacter* and *Proteus,* now carry *R* factors.

(These organisms are all gram-negative bacteria; *R* factors seem not to be transferable to the gram-positive bacteria, which include streptococci and staphylococci. A somewhat similar form of transmissible resistance has been discovered in staphylococci, however. There are cytoplasmic genes, or plasmids, in some staphylococci that determine the production of penicillinase, an enzyme that inactivates penicillin. Richard P. Novick of the Public Health Research Institute in New York and Stephen I. Morse of Rockefeller University recently showed that these plasmids can be transduced to drug-sensitive staphylococci both in the test tube and in laboratory animals. The actual clinical importance of this process remains to be determined.)

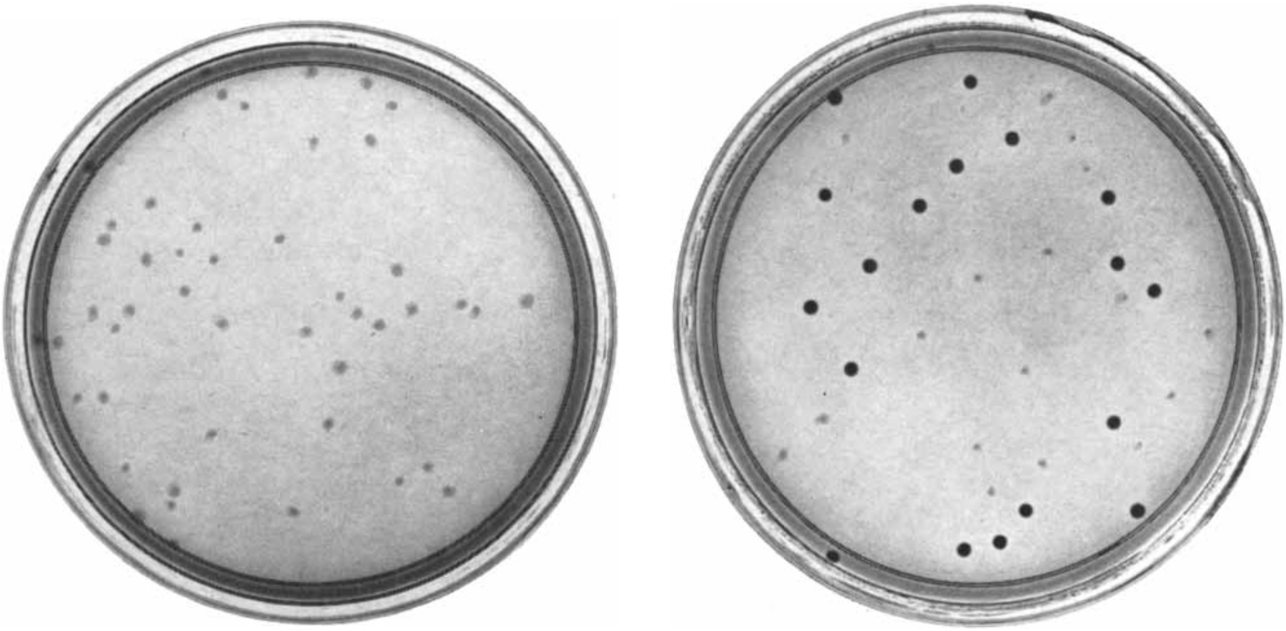
The *R* factors seem to be acquiring resistance genes for an increasing number of antibiotics. The original factors, it will be remembered, imparted resistance to sulfanilamide, streptomycin, chloramphenicol and tetracycline. In 1963 G. Lebek of West Germany discovered a factor that causes resistance to these four drugs and also to the neomycin-kanamycin group of antibiotics. In 1965 Mrs. Datta and Kontomichalou reported a new determinant of resistance to aminobenzyl penicillin (ampicillin). In 1966 H. W. Smith and Sheila Halls of the Animal Health Trust in Britain found factors imparting resistance to the synthetic antibacterial drug furazolidone. This year David H. Smith of the Harvard Medical School reported *R*-factor-controlled resistance to gentamycin and spectinomycin. We must assume that additional drug-resistance determinants will appear and proliferate as new antibiotics come into use.

This is implicit in the mechanism of infectious resistance. *R* factors are common in *E. coli,* which are often present in the intestinal tracts of human beings and animals. When a person or an animal becomes infected with a susceptible disease organism, the *R* factor is readily transferred to the new population. Although the frequency of transfer of *R* factors is not high even in the laboratory, and is reduced by the presence of bile salts and fatty acids in the intestine, recipient bacteria bearing the *R* factor are given a selective advantage as soon as drug therapy begins, and they soon predominate.

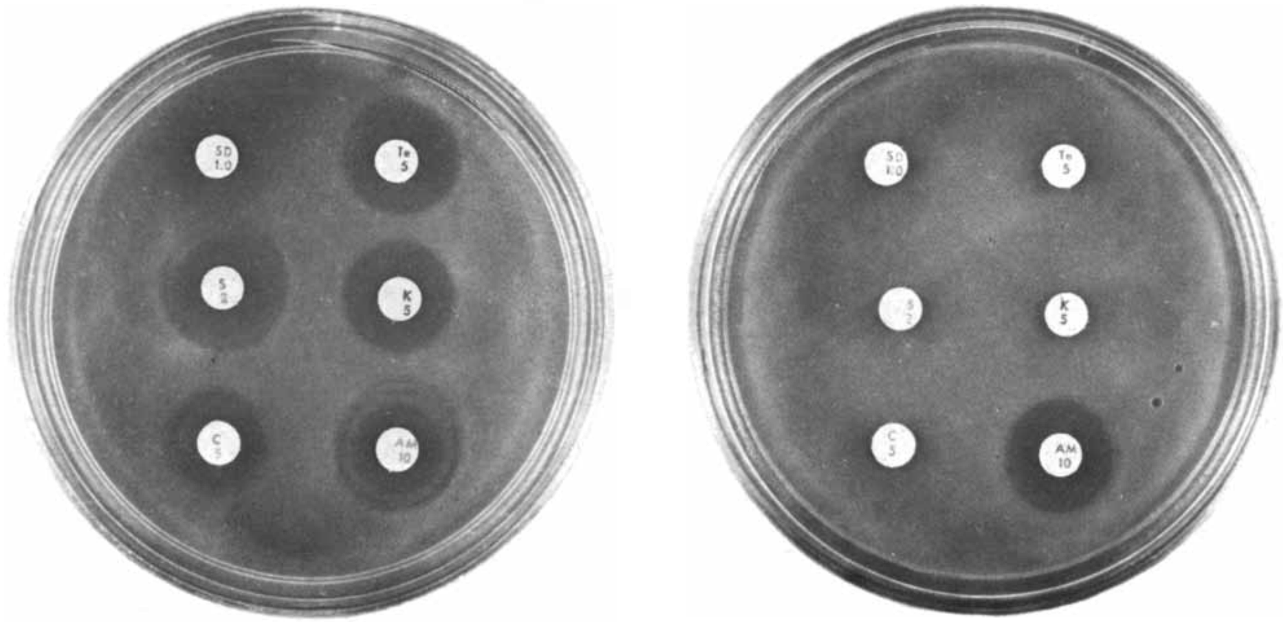
In addition to being ineffective and helping to spread resistance, "shotgun" treatment of an infection with drugs to which it is resistant causes undesirable side effects. It is therefore important to culture the causative agent, determine its drug-resistance pattern and institute treatment with a drug to which it is not resistant; that is the only way to combat the multiple-resistance strains. As more is learned about the *R* factor, new forms of therapy may be developed—possibly utilizing the acridine dyes, which attack drug-resistant as well as sensitive cells and can also eliminate *R* factors from cells.

In many parts of the world antibiotics are routinely incorporated in livestock feeds to promote fattening and are also used to control animal diseases. Anderson and Mrs. Datta have shown clearly that the presence of antibiotics in livestock exerts a strong selective pressure in favor of organisms—particularly salmonellae—with *R* factors and plays an important role in the spread of infectious resistance. Meat and other foodstuffs are also treated with antibiotics and synthetic drugs as preservatives in many countries, and this too may help to spread *R* factors and carry them to man. Unless we put a halt to the prodigal use of antibiotics and synthetic drugs we may soon be forced back into the preantibiotic era of medicine.

One final note. Typhoid, cholera and plague bacilli are obviously much more difficult to combat if they are resistant to drug therapy. There are grounds for believing that the military in some countries are investigating the potentialities of *R* factors as weapons of bacteriological warfare.



SENSITIVITY TEST conducted in Smith's laboratory at Harvard demonstrates infectious drug resistance. A culture of *Salmonella typhimurium* with an *R* factor controlling resistance to four drugs is mixed with drug-sensitive *E. coli*. A portion of the mixed culture is immediately plated on a medium containing the drugs (*left*). Only *Salmonella* colonies (*gray*) appear. After the mixed culture has incubated, the plating procedure is repeated, and now *E. coli* colonies (*black*) grow as well (*right*): the *R* factor was transferred.



SIMILAR TEST is performed with filter-paper disks impregnated with six drugs: sulfadiazine (*SD*), tetracycline (*Te*), streptomycin (*S*), kanamycin (*K*), chloramphenicol (*C*) and ampicillin (*AM*). A culture of *E. coli* was at first sensitive to all six, as shown by the dark zones around each disk where the bacteria have been killed (*left*). After the culture was incubated with a strain of *Klebsiella*, taken from a patient, that was resistant to all the drugs but ampicillin, the *E. coli* too were resistant to all but ampicillin (*right*).

THE EARLIEST APES

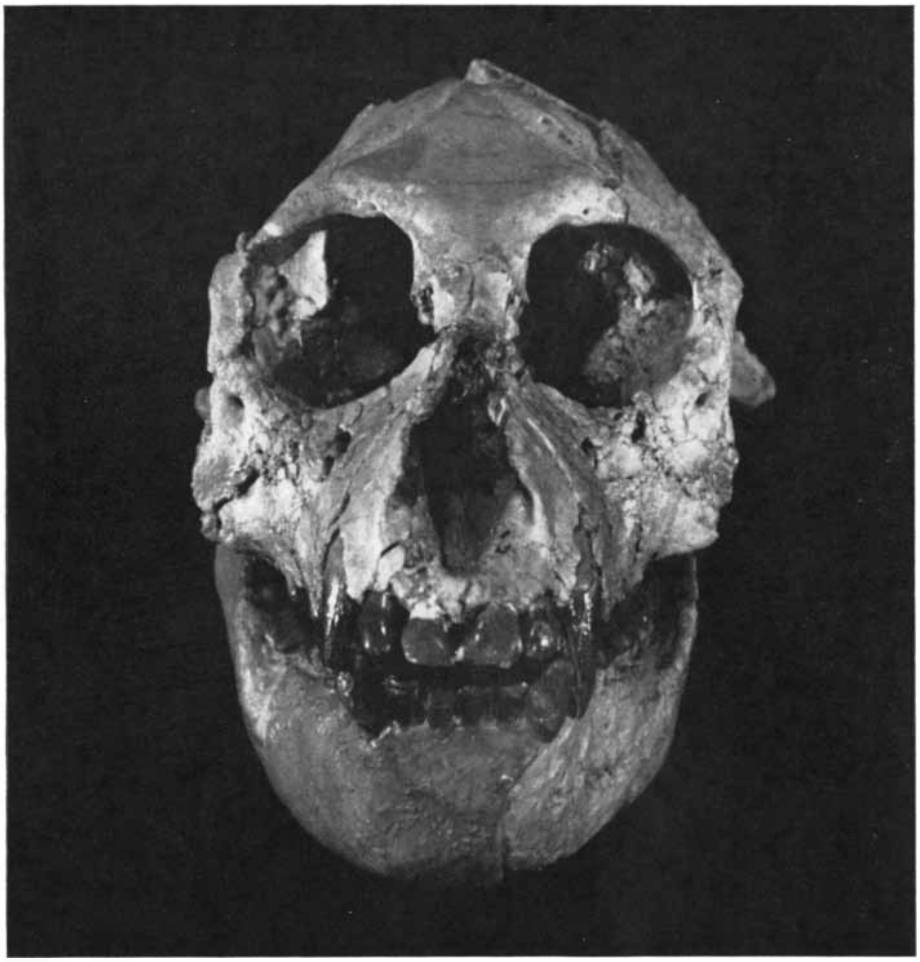
What kind of animal gave rise to modern apes and man? The answer has been brought considerably closer by the unearthing in Egypt of the skull of an ancestral ape that dates back 28 million years

by Elwyn L. Simons

When it was that the early primates of the Old World first gave rise to the hominoid line from which the modern apes and man evolved is a question that has not had a satisfactory answer since it was first asked a century ago. Just where hominoid primates first evolved and why they evolved at all are rather more recent questions, but they too have lacked generally accepted answers. All three questions now appear to be answerable on the basis of evidence provided by fossil discoveries made during a recent series of Yale University expeditions to the Fayum region of Egypt. Our most exciting discovery, an almost complete primate cranium dating back between 26 and 28 million years, is the oldest ape skull ever found. It belongs to an individual of the newly established genus *Aegyptopithecus*. Studies of the skull, of abundant jawbones and teeth, of scarcer limb bones and of a few other skull fragments that represent this genus and five more genera of Fayum primates have added substance and precision to what was formerly a scant and hazy chapter in the record of primate evolution.

Only 60 miles southwest of Cairo, the Fayum is an area in which fertile fields gradually give way to desert badlands surrounding a large, brackish body of water called Lake Qàrûn. (The name of the region is derived from the ancient Egyptian word for lake: *pa-yom*.) The desert buttes and escarpments have been a fossil-hunter's paradise since late in the 19th century, when a few commercial collectors and professional paleontologists first explored the area. The Mediterranean coast is 120 miles away, but during Oligocene times it cut across the Fayum. There large rivers entered the sea and gradually built up layers of sand and mud that reach a total thickness of more than 600 feet. What is desert today was then a well-watered landscape in which forest was interspersed with open glades. Many fossilized tree trunks have been found; some are nearly 100 feet long. In trying to reconstruct the appearance of the Fayum during the Oligocene one gains the overall impression of a tropical forest along the banks of meandering rivers.

The fossil remains show that fishes, turtles, dugongs, crocodiles and their narrow-snouted cousins, false gavials, lived in the rivers. In the open areas there were carnivores the size of weasels,

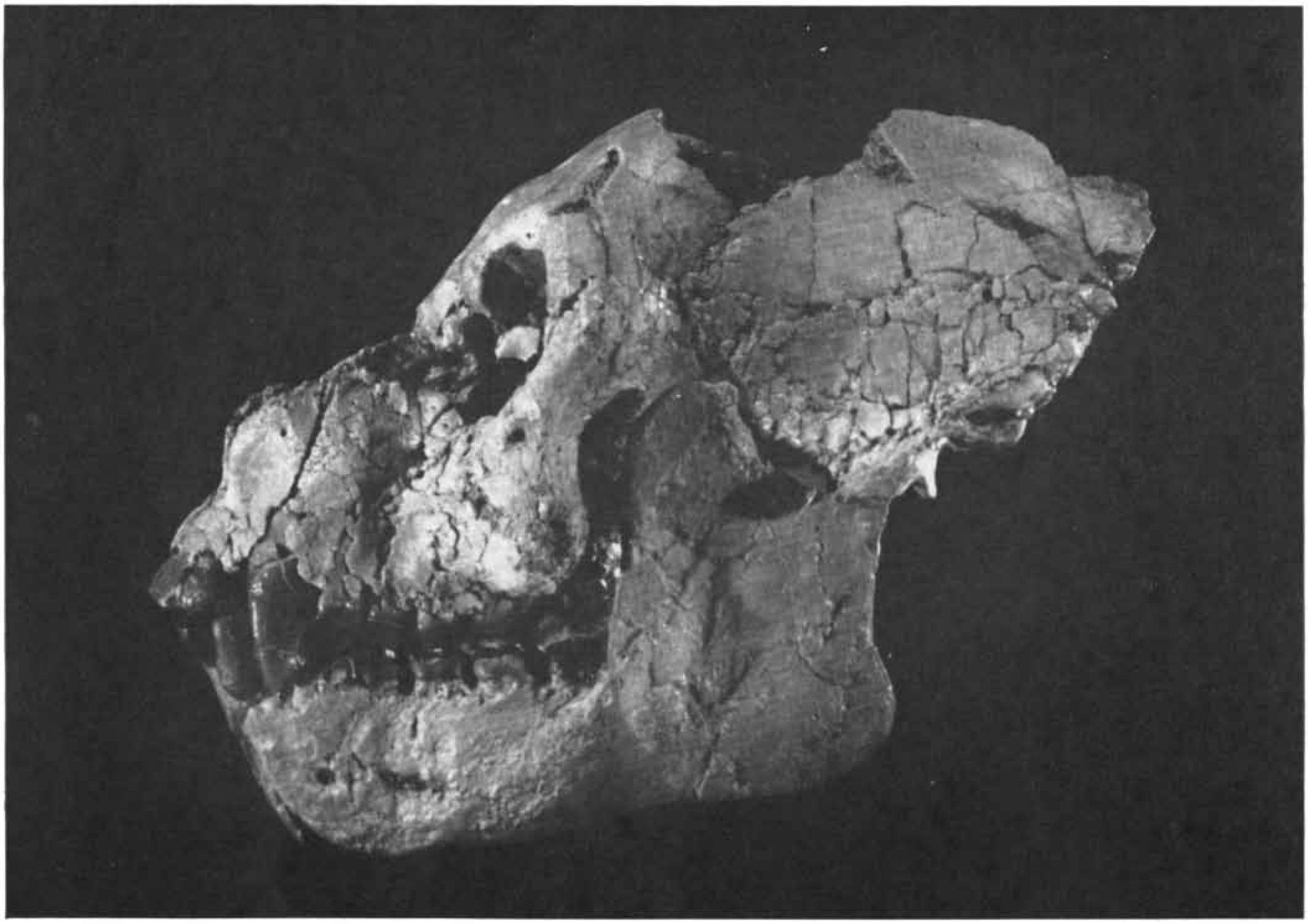


EARLIEST APE SKULL, found in the Fayum region of Egypt last year, comes from a stratum of later Oligocene age. The front and side photographs show it one-half larger than life size. The lower jaw is a restoration based on jaw fragments not found in association small and large cousins of the modern elephant and a four-horned herbivore as big as a modern rhinoceros. The forest was inhabited by bats, perhaps by tiny rodents and by several species of primates. The fossilized bones of the primates are found in the sands of the former riverbeds. Of the scores of primate jaws we have uncovered in these deposits, only one, judging by the eruption and wear of the teeth, belonged to an individual that had lived to a ripe old age. These fossils apparently originated with a young animal's misjudged leap through the trees beside the river or its carelessness while drinking.

Hunting for fossil primates in the Fayum is largely a matter of examining two specific sedimentary layers called the upper and lower fossil-wood zones. The upper zone lies some 300 feet above the lower, and the fossil-rich sites are found on slopes adjacent to an escarpment of volcanic rock above Lake Qârûn. The volcanic rock, which lies some 250 feet above the upper fossil-wood zone, has been dated by the potassium-argon method. Actually there have been two age determinations; one made at the University of California at Berkeley gives a figure of 24.7 ± .4 million years, and one made at Yale 27 ± 2 million years. Either date approximates the end of the Oligocene period, placing the upper fossil-wood zone in the later Oligocene. Comparisons with fossils in Europe suggest that the lower fossil-wood zone is perhaps six million years older and thus belongs to the early Oligocene.

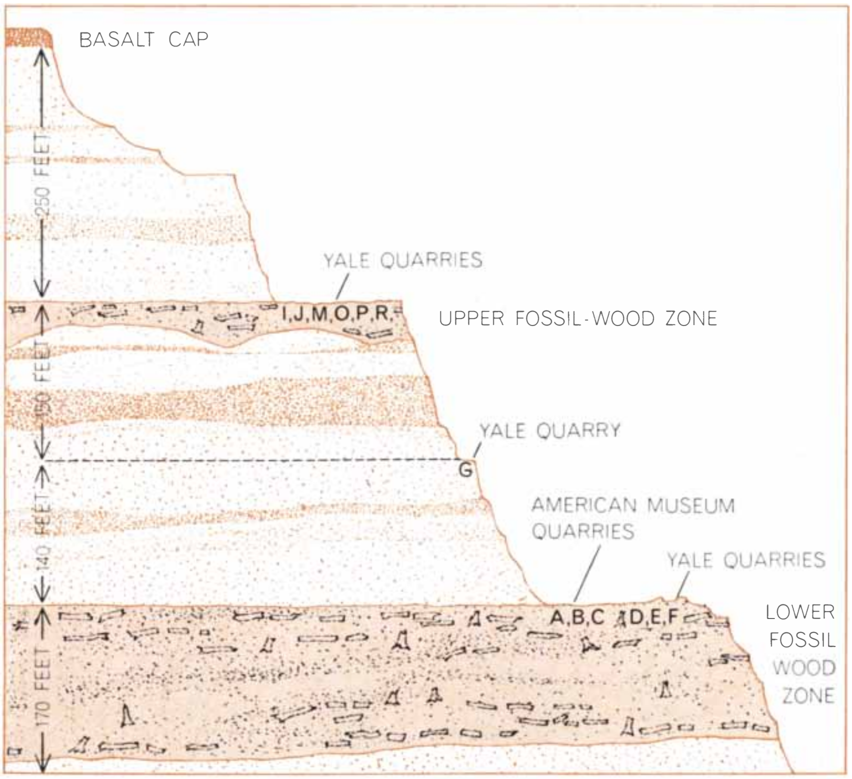
The search for fossils is aided by the fact that in many places the desert winds have blown away the sand and soil and laid bare the upper surfaces of buried bones [*see lower illustration on page 31*]. The winds had plagued earlier Fayum fossil-hunters, but to us they have been a blessing in more ways than one. When we have quarried for fossils, our crews have been able simply to remove overlying rock or to sweep away the "desert pavement," or surface stones; the wind has then scoured tons of unconsolidated sediments out of the quarries, leaving the fragile fossils still in place. Once the wind has done its work it is still necessary to clear the fossils further and to protect and remove them. Apparently there has been little percolation of groundwater through the Fayum sandstones, with the result that the bones have little or none of the mineral content characteristic of most vertebrate fossils. We have found, however, that modern synthetic resins make excellent "instant" fossilizers.

Until the Yale expeditions to the Fayum were inaugurated under my direction in 1961 the entire inventory of primate fossils from the area was seven fragments of bone and teeth. These fragments nonetheless played a major role in the development of modern theories about primate evolution. The greatest service the Fayum expeditions may have performed is that they have uncovered enough new fossils to correct several misconceptions arising from the fact that the



with the cranium; the four incisor teeth of the upper jaw are also restorations. Generally monkey-like, the skull belongs to a species of ape recently named *Aegyptopithecus zeuxis* by the author. The species was probably ancestral to the dryopithecine apes of the Miocene (*see illustration on page 35*). The latter, once abundant in Africa and Eurasia, apparently gave rise to modern apes and man.

FAYUM REGION, 60 miles southwest of Cairo, is noted for its Oligocene fossils, which are found along the slope that rises from Lake Qârûn, 150 feet below sea level, to the top of the 1,000-foot-high Qatrani escarpment, which is capped with post-Oligocene volcanic rock.



FOSSIL-RICH QUARRY SITES lie at various levels in thick Fayum deposits of unconsolidated sandstones and mudstones, seen here in a schematic cross section. Most of the animal remains have been found in two strata that also contain fossilized wood. The bones of primates are quite scarce; they have been found only in the four quarries E, G, I and M.

original sample of fossils was so small.

The recent discoveries are seen most clearly against a background of the earlier interpretations that our findings have confirmed or modified. I shall begin my review of these earlier interpretations with two Fayum primate genera that are *not* apes. They belong to the family Parapithecidae, a group that may be ancestral to the Old World monkeys.

One genus of this family accounts for more fossils than any other primate found in the Fayum beds. It is the genus *Apidium*, represented by two species: *Apidium phiomense* and *A. moustafai*. The first fossil of the genus—a lower jaw—was discovered early in this century by the German fossil-hunter Richard Markgraf, who was working for the American Museum of Natural History. The generic name, proposed in 1908, is derived from Apis, the sacred bull of Egypt. This odd choice was made because at first the specimen was not clearly recognized as belonging to a primate. Paleontologists have gradually come to agree, however, that *Apidium* may be related to the evolutionary line from which the Old World monkeys evolved or to *Oreopithecus*, an apelike fossil primate found in Italy. As a result of our six seasons of work, *Apidium* is now represented by parts of more than 50 lower jaws and four upper jaws. *Apidium* had a short face and was evidently about the size of a squirrel monkey. Like this monkey of the New World, it had 36 teeth arranged according to the "dental formula" that is written in anatomical shorthand as 2 : 1 : 3 : 3. This is to say that on each side of the upper and lower jaw there were two incisors, one canine, three premolars and three molars [*see illustration on page 34*].

The other member of the family Parapithecidae found in the Fayum is the species that gave the family its name: *Parapithecus fraasi*. This fossil primate was also discovered by Markgraf; it was described and named in 1910 by the German paleontologist Max Schlosser, who had become acquainted with fossil primates while studying specimens from North America in a collection at Yale that had been assembled by Othniel Marsh. What Markgraf found was both sides of a lower jaw, cracked at the midline but otherwise apparently complete except for one tooth. Counting the specimen's teeth, Schlosser concluded that the animal had the same dental formula—1 : 1 : 3 : 3—as certain living "prosimians" such as the tarsiers. He and most later students interpreted the crack at the midline of the jaw as further evidence supporting this view; among prosimians the suture between the two halves of the lower jaw rarely fuses as it does early in life among the higher primates. Together with the specimen's small size—about the same as the jaw of a tarsier or a squirrel monkey—these were clues enough for Schlosser. He concluded that *Parapithecus* represented a transition between the early prosimians and the higher primates. Later, counting the teeth in a different way, Schlosser and others decided that the animal had affinities with man.

With the advantage of hindsight and many more specimens to study, it is easy to see how Schlosser's findings were in error. In fact, his conclusions exemplify the difficulties inherent in reaching wide-ranging evolutionary conclusions on the basis of a single fragmentary specimen. One can scarcely blame Schlosser for expressing his opinion before other specimens had been found, but if he had been able to wait, he would never have been deceived. For example, additional *Parapithecus* jaws we have found show that both sides of the jaws are solidly fused in front, even among the juvenile specimens, as they are in the higher primates. Moreover, the *Parapithecus* dental formula is like that of *Apidium:* 2 : 1 : 3 : 3. The jaw discovered by Markgraf had evidently broken apart at the front suture at the time of burial or of discovery. Somehow the two side incisors and their supporting bone were lost, leaving posterity with the false impression that the specimen had only one pair of front teeth.

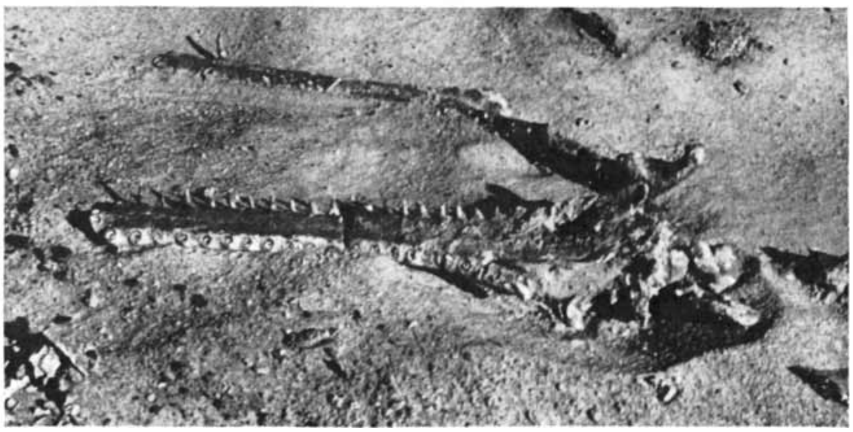
The fact that both of these Oligocene primates have the same tooth count as New World monkeys should not be considered evidence of any particularly close relation with such monkeys. There is no theoretical reason why the ancestors of Old World monkeys should not once have had an extra premolar all around. Indeed, it is the exception rather than the rule for all members of a mammalian suborder to have the same dental formula. Actually the formula of *Parapithecus* and *Apidium* is the same as that of an even earlier forebear of the Old World primates: *Amphipithecus,* found in an Eocene formation of Burma [see "The Early Relatives of Man," by Elwyn L. Simons; SCIENTIFIC AMERICAN, July, 1964].

Almost certainly the oldest of all the Fayum primates is *Oligopithecus savagei,* an animal that was unknown until our first season of work in 1961. *Oligopithecus* is represented by the left half of a lower jaw from which both incisors and the rear molar have been lost; the jaw was found in the lower fossil-wood zone. Unlike *Parapithecus* and *Apidium,* this animal apparently had the same advanced dental formula as the Old World monkeys, the apes and man (2 : 1 : 2 : 3). *Oligopithecus* appears to be the descendant of a primate that had arrived in the region in the Eocene period. Its molars, although they clearly can be classified as belonging to an advanced primate, are related in form to the molars of the primitive prosimian family Omomyidae, whose fossil remains are found in Eocene formations of Europe, Asia and North America. Such a generalized tooth structure agrees well with the antiquity of the strata that contain the remains of *Oligopithecus,* which were probably laid down more than 32 million years ago.

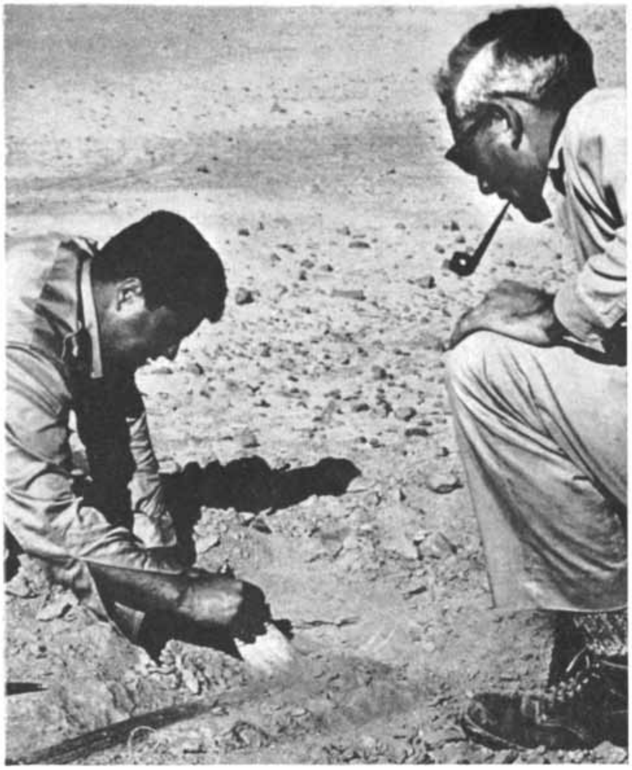
Perhaps the best-known Oligocene primate is *Propliopithecus haeckeli,* another of Markgraf's discoveries. In giving it this name Schlosser was expressing his belief that the animal, then represented by two nearly complete halves of a lower jaw, could have been ancestral to the fossil gibbon *Pliopithecus,* found in younger formations of the Miocene and Pliocene in France. Later workers agreed with this assessment, and *Propliopithecus* was generally accepted as an early ape, ancestral to the modern gibbons. As we shall see, this is a position it should probably not occupy.

As a result of our fossil collecting, the remains of *Propliopithecus* now include two more lower jaws and about a dozen teeth. The site of Markgraf's discovery cannot be located with certainty today. Some of our *Propliopithecus* specimens, however, come from the site we call Quarry G. In terms of stratigraphy Quarry G lies about halfway between the

REMOVAL OF STONES that form a protective layer of "desert pavement" on the surface of a quarry lets the Fayum windstorms blow the loose grains of sand away, laying fossils bare.



FOSSIL JAWBONES exposed by the wind are those of a fish-eating crocodilian, the false gavial. Reptiles, fishes and mammals lived in the rivers of the Fayum in Oligocene times.



SKULL OF A SAWFISH, hardened after an application of glue, is brushed clean of sand grains (*left*) by Grant E. Meyer as he prepares to remove the fossil from the rock that surrounds it. Next (*center*) Meyer pours water on the fossil as Thomas F. Walsh holds

lower and the upper fossil-wood zone. The *Propliopithecus* fossils from this location must therefore be younger than *Oligopithecus* from the lower zone. The same may be true of Markgraf's find.

In any case, the teeth of the proposed ancestral gibbon show few exclusively apelike characteristics. Among the apes the front premolars are elongated and the canines are large. In the fossil apes of the Miocene, and in the modern gorilla and orangutan, the three molars at the rear of the jaw usually increase in size from front to back. None of these characteristics is evident in *Propliopithecus.* Moreover, to judge from the tooth sockets and the adjacent bone, the animal's incisors appear to be placed vertically rather than jutting forward as they usually do in apes and monkeys.

These and a few other details of *Propliopithecus'* dentition make the animal seem more closely related to man's family, the Hominidae, than to either of the two families of apes: the Hylobatidae (which include the gibbon and the siamang) and the Pongidae (which include the chimpanzee, the gorilla and the orangutan). Indeed, some students have taken this hominid trait in *Propliopithecus* to mean that apes ancestral to the human line had branched off the main line of ape evolution as early as Oligocene times. I would prefer an alternative interpretation, at least for the present.

Still another of Markgraf's discoveries was described by Schlosser; it was named *Moeripithecus markgrafi* in honor of the indefatigable fossil-hunter. The original specimen, preserved in the paleontological collection at Stuttgart, consists of a juvenile jaw fragment in which only the first and second molars are in place. In 1963 I visited Stuttgart to compare the original with several of the individual teeth attributable to *Propliopithecus* that we had found in Quarry G. This comparison and later study of other specimens convinces me that almost every consideration on which Schlosser based his designation of *Moeripithecus* as a genus is attributable to the fact that the original jaw fragment came from a young animal whose molars had not been much worn down. The jaw appears to belong to a species of the genus *Propliopithecus,* although not the species *P. haeckeli.* Consequently *Moeripithecus* should be dropped as a genus and the fossil assigned to the genus *Propliopithecus.*

During our third season in the Fayum, one of the best fossils to be collected from Quarry I in the upper fossil-wood zone was a full lower jaw, fused at the front suture and containing almost a full complement of teeth. The incisors were gone, but fortunately the bony sockets that had held them were still intact. The jaw differs from the jaws of most of the other Fayum primates in having elongated first premolars and relatively massive canines with thick roots. These are apelike characteristics. Still other characteristics, including a quite small third molar and a decrease in the depth of the jaw from front to back, are reminiscent of the gibbons. I have named this species, which was about half the size of a modern gibbon, *Aeolopithecus chirobates.* It is possible that this animal, rather than *Propliopithecus,* was the Oligocene forebear of the full-fledged gibbons that are found as fossils in Miocene formations of East Africa and Europe dated eight to 10 million years later. Both *Aeolopithecus* and *Propliopithecus,* however, may have been diminutive early apes that left no descendants.

The largest Fayum primate, to which I have given the name *Aegyptopithecus zeuxis,* was known until recently only from four incomplete lower jaws and half a dozen individual upper teeth that were also found at Quarry I in the upper fossil-wood zone. The size of the animal's lower jaw is about equal to that of a gibbon; it is nearly a third larger than the jaw of *Propliopithecus.* Several characteristics of the teeth make it clear that this new genus of upper Oligocene

a basin for mixing plaster. Finally (*right*) layers of paper cover the damp specimen. They will keep the plaster, which protects the fossil during transit, from adhering to its surface.

primate could have evolved from a species of *Propliopithecus* during the several million years or so separating it from the fossil remains of the earlier genus. The evolution had been in a direction that gives the younger animal a close resemblance to the still later apes of the genus *Dryopithecus,* which were a major element of the Old World primate population in Miocene times.

Students of primate evolution today generally agree that it was from the dryopithecine apes of the Miocene period that the lines of development arose leading on the one hand to the great apes and on the other, by way of *Ramapithecus* and *Australopithecus,* to modern man's immediate precursor *Homo erectus.* It is therefore of great interest to discover an ape with teeth particularly like those of the earliest species of *Dryopithecus* but that is something between eight and 12 million years older. The earliest dryopithecine is another fossil from Africa, *Dryopithecus africanus* ("Proconsul"), a skull of which was discovered in a Miocene formation of Kenya by Mary Leakey in 1948. Until recently this was the only known skull of a fossil ape.

Aegyptopithecus, although no larger than a gibbon, has teeth much like a gorilla's; the canines are large and the front premolars are elongated. From front to back the three lower molars increase markedly in size; the entire jaw is more apelike than the jaw of *Propliopithecus* and is much deeper under the canines. It quickly became apparent to us that, however useful our other fossil discoveries might be in disposing of old misconceptions and clarifying the picture of Oligocene primate life in the Fayum, our discovery of *Aegyptopithecus* could provide a major contribution to the understanding of early primate evolution. Here was an animal of the right form and the right age to be ancestral to the dryopithecine apes of the following epoch. It could thus occupy an early position in man's lineage and even perhaps be the direct forebear of apes such as the modern gorilla as well.

Late in the 1966 season my research associate Grant E. Meyer was making a surface reconnaissance of Quarry M in the upper fossil-wood zone. He came on the frontal bone and both parietal bones of a skull—an exciting find because six seasons of work had yielded only a few fragments of cranial bone. Meyer at once soaked the bones and the surrounding matrix with glue so that a sizable chunk of quarry floor could be safely dug out, covered with plaster and burlap and shipped to our laboratory at Yale for the delicate job of cleaning. It would be hard to say whether our surprise or our delight was the greater when the cleaning process revealed that Meyer had found not just a few skull fragments but a nearly whole skull of *Aegyptopithecus* from which only portions of the top and bottom of the skull and the four incisor teeth proved to be missing [*see illustrations on pages 28 and 29*].

With the world's oldest-known ape skull added to the rest of the fossils available for analysis, we return to the three questions raised at the beginning. As to when it was that the hominoid line leading to modern apes and man first evolved from a more generalized Old World primate, the almost inescapable answer today is during the Oligocene epoch. At least with respect to the great apes and man, the specific primate involved in the branching is *Aegyptopithecus,* although *Aeolopithecus* is perhaps a twig pointing toward the lesser apes. In turn, the primate stock from which the main branch grew could be the earlier fossil form *Propliopithecus.* An even earlier connecting link could be *Oligopithecus* of the early Oligocene, with its teeth that bear resemblances to Eocene primates as well as to most later monkeys and apes.

Obviously the second question, as to where these events took place, has already been answered. They certainly occurred in this one area of forest and glade where nameless rivers entered the sea. Presumably they were also taking place elsewhere to the west and south in Africa as boisterous populations of proto-monkeys and near-apes flourished and evolved over a span of scme 12 million years. An accident of fossil preservation requires that, if we are asked, "Exactly where?" we must reply, "In the Fayum." Someday the answer may be much more wide-ranging.

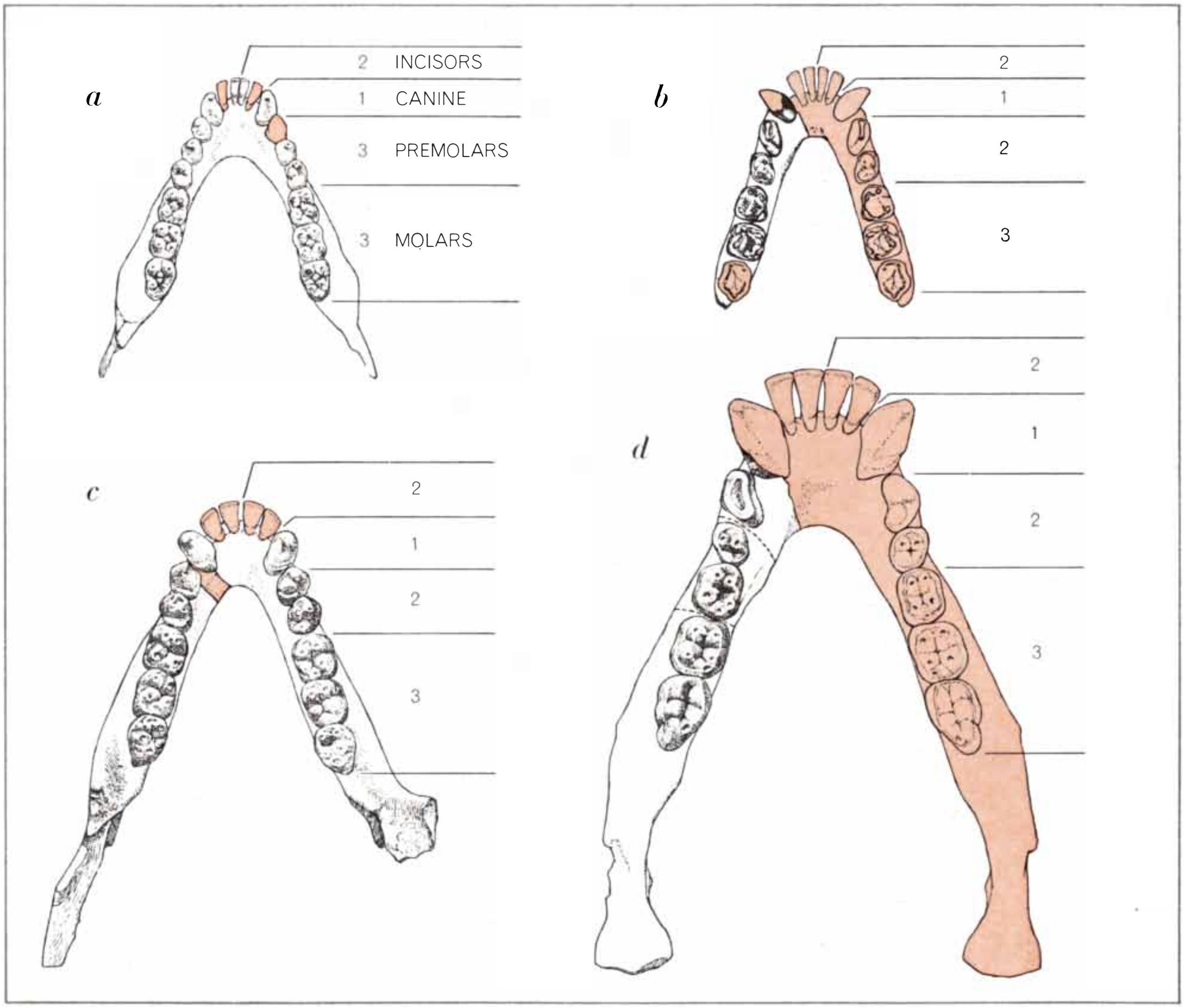
It is well to remember in this connection that almost nothing is known of the Paleocene and Eocene animals of Africa, although together the two epochs comprise nearly half of the length of the Age of Mammals. Africa's fossil fauna in Oligocene and Miocene times, although better known, remain painfully scanty. The evolutionary scheme I have proposed here and the fossil genera on which it is founded represent a rationale based on chance fossil preservation and discovery. The evidence is still susceptible to a number of alternative interpretations. Many early African primates must have existed about which we now know nothing. No one can say if some of them were more directly related to living man and the apes than any we now know.

There remains the question of why it

is that hominoid primates evolved. The answer, it seems to me, is that the Oligocene primates' arboreal way of life, involving feeding on leaf buds and fruits near the end of branches, gave survival value to certain kinds of dexterity. If this suggestion regarding the arboreal life is to be useful in assessing the Fayum fossils, it is necessary to digress briefly and examine some surprising parallels between the behavior of some modern apes and that of certain lower primates, specifically the large lemurs *Indri* and *Propithecus*.

These large lemurs, familiarly known as indris and sifakas, are specialized in various quite distinct ways for a life of arboreal foraging; the same is true of the lesser apes, in particular the gibbon and the siamang of Asia. The gibbon and the siamang are exclusively tree-dwellers and primarily eaters of insects and fruit. Their ability to move out among small branches in order to feed while in a suspended position, as well as their dexterity in swinging by their arms, is extraordinary. Among the apes of Africa the arboreal way of life is less extreme; the gorilla spends more time on the ground than in the trees, although in evolutionary terms this is a recent adaptation. The chimpanzee is mainly terrestrial in locomotion. Its dexterity when feeding in the branches of trees, however, is exceeded only by that of the Asian apes. Nor is large size an absolute barrier to arboreal life: the orangutan spends all its years as a tree-dwelling forager, although the male may weigh 160 pounds at maturity.

The dexterity of the large lemurs in tree-climbing, clinging and leaping is equal to that of their more advanced primate kin. These animals' snouts are somewhat flattened, and their eyes are far enough forward in the skull to add depth perception to their manual dexterity and locomotor versatility. Yet no one could anatomically confuse the indris and sifakas with the apes. Their dental formula is different, and so are many other details of skull, limb and hand. Moreover, one of them—the sifaka—has a long tail. The resemblances are in behavior and in locomotion, not in anatomy. Like the gibbons, the two large lemurs form small social groups and



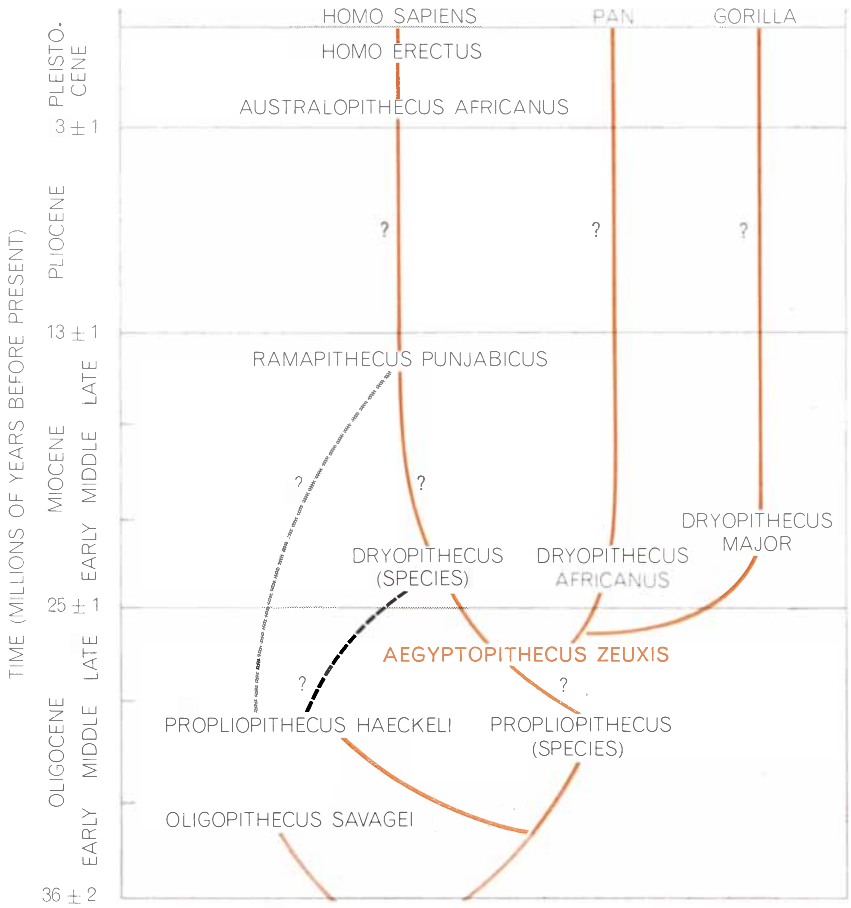
LOWER JAWS of four Fayum primates illustrate the relative size of the fossils and the difference between the New World and Old World "dental formula." ***Apidium*** **(*a*) is a small parapithecid and the most abundant Fayum fossil primate; the number of its teeth is the same as that of New World monkeys.** ***Oligopithecus*** **(*b*) is probably the oldest Fayum primate. Like** ***Propliopithecus*** **(*c*) and the largest Fayum primate,** ***Aegyptopithecus*** **(*d*), its tooth count is the same as that of all Old World monkeys, the apes and man. The teeth and jawbones shown in detail are based on fossil specimens; where teeth or bones are in color they represent reconstructions.**

communicate with loud, hooting cries. Seeing them in the trees, clinging with their torsos erect, or on the ground moving on their hind limbs (the sifaka curls its tail neatly out of the way on such occasions), one is struck by the similarity between these prosimians and the fossil apes of the Fayum, whose pattern of life was apparently much like theirs. The large lemurs demonstrate that, even at the quite primitive prosimian level of primate evolution, striking behavioral advances and locomotor adaptations are possible. It seems evident that the apes first arose from one such adaptive shift; the Fayum apes are apparently not far from that point.

It should come as no surprise, then, to learn that among the fossil discoveries in Quarry I are a number of tailbones, almost certainly assignable to *Aegyptopithecus*. Speaking anatomically, it was to be expected that some ancestral primate would cross the threshold separating monkey from ape and still bring its monkey tail along. The successful tree life of the tailed lemur, however, helps us to realize that possession of a tail was not necessarily a handicap to *Aegyptopithecus*' adaptation as an arboreal ape.

The skull of *Aegyptopithecus*, and also three fragments of frontal bone we have found (belonging to at least two different species), show that the Fayum primates' eyes had shifted forward, with a consequent enhancement of depth perception. *Aegyptopithecus* has a narrow snout (still long by ape standards), some expansion of the forebrain and a related reduction in the dimensions of the brain's olfactory lobes [*see illustrations on pages 28 and 29*]. These are changes in form that are correlated with a greater predominance of the visual sense over the olfactory, and they are typical adaptations with survival value for arboreal life. The foot bones and many other limb bones we have found, which probably belong mainly to *Apidium*, are suggestive of adaptation to life in the trees. The few that appear to belong to *Aegyptopithecus* suggest the same habitat.

To me it seems probable that the selective pressures of millions of years in the trees forced a comparatively primitive population of the kind represented by the anatomically generalized early *Oligopithecus*—with its echoes of even more primitive Eocene forebears—along the road to apehood. That the pressures were effective is shown by the evolution en route of several anatomically intermediate species of *Propliopithecus*. When the pressures culminated near the



TENTATIVE FAMILY TREE prepared by the author shows alternate ways in which the Oligocene primates of the Fayum may be connected with the main lines of ape and human evolution. The ancestral position of *Oligopithecus*, the earliest in the group to have an advanced dental formula, is uncertain; the animal therefore is put to one side of the main line that leads to various species of *Propliopithecus* in the mid-Oligocene. These are shown to be most probably ancestral to *Aegyptopithecus* of the later Oligocene, the genus that in turn is proposed as the most probable forebear of the dryopithecine apes of the next geological epoch, the Miocene. Lesser probabilities are that one species of *Propliopithecus*, *P. haeckeli*, gave rise to those dryopithecines from which *Ramapithecus* and the hominid line arose (*broken black line*) or was directly ancestral to *Ramapithecus* (*broken gray line*). In either event, *Aegyptopithecus* remains ancestral to the two dryopithecine species, *D. africanus* and *D. major*, the apparent forebears of the chimpanzees and gorillas respectively.

end of the Oligocene, the evolutionary process had brought forth an anatomically ideal prototype for the dryopithecines in the form of *Aegyptopithecus*.

The primitiveness of such hand, foot and limb bones of dryopithecines as are now known has allowed scholars to characterize the dryopithecines somewhat flippantly as animals with the heads of apes attached to the bodies of monkeys. If I were to characterize *Aegyptopithecus* in the same fashion, I would have to speak of the skull of a monkey equipped with the teeth of an ape. Why not? If my analyses, both of the evolutionary sequence and of the skull's anatomy, are correct, this animal was an oversized tree-dweller, still carrying a tail in spite of anatomical advances such as suture-closing and hominoid teeth. The animal's braincase, in relation to its face, was smaller than that of any subsequent hominoid. The bone behind the eyes formed a less complete closure than it does in hominoids or in Old World and New World monkeys. The auditory canals are not enclosed in an external tube, as they are in all the later Old World monkeys, the apes and man, and the tympanic ring is fused in a manner resembling the prosimian lorises and the New World monkeys. But what is more important than the primitive anatomical traits of *Aegyptopithecus* is the clear stamp of the higher primates to be seen in it. The animal was evidently pursuing an arboreal pattern of life directing it along the evolutionary path leading from lemur-like and monkey-like forms to apes and perhaps ultimately to man.

X-RAY STARS

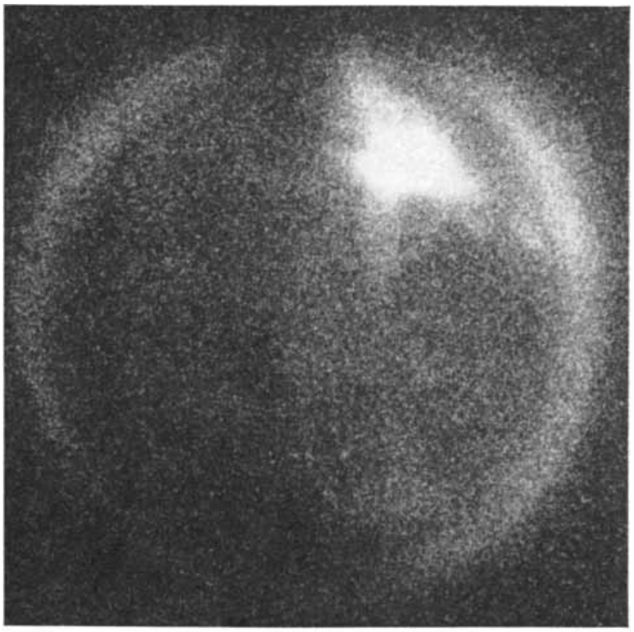
Rocket-borne instruments have detected a number of objects that are intense emitters of X rays. One of them is a star that produces as much energy in the form of X rays as the sun does at all wavelengths

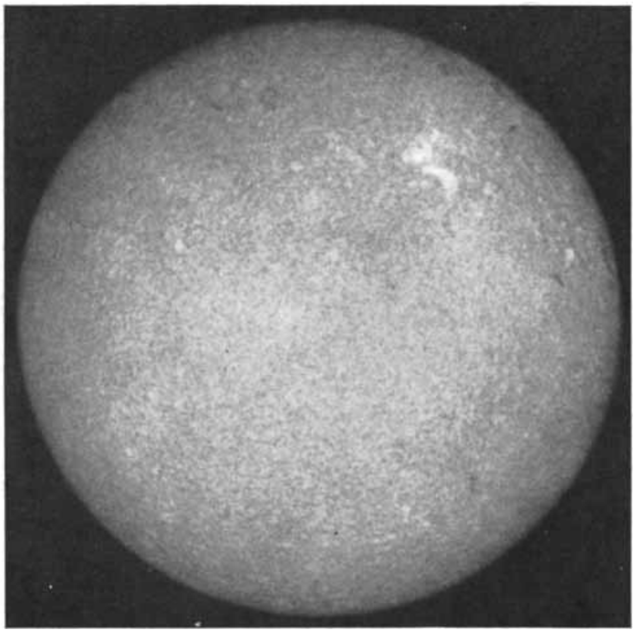
by Riccardo Giacconi

For the past five years astronomers have been regarding the universe through a new window that has disclosed totally unexpected phenomena. The window of visible light through which man has always looked into space shows only a small part of the events occurring outside the atmosphere of our planet. When Karl G. Jansky opened a second window 35 years ago by discovering that his radio receiver was detecting radio waves from outer space, a new world of phenomena came into view. Radio telescopes have since then disclosed the existence of such formerly unknown celestial objects as radio-emitting gas clouds and quasars. We are now looking through a third window in another part of the radiation spectrum that reveals a new class of objects best described as X-ray stars, because X rays are their dominant radiation, overwhelmingly greater than their emission of light and radio waves.

Although interstellar space is suffused with radiation over the entire electromagnetic spectrum, from the extremely short waves of gamma rays and X rays to the very long radio waves, relatively little of the cosmic radiation reaches the earth's surface. Our atmosphere screens out most of the wavelengths [*see top illustration on pages 38 and 39*]. In particular the atmosphere is completely opaque to wavelengths shorter than 2,000 angstrom units. Hence X radiation from space can be detected only by sending instruments to the outer regions of our atmosphere in balloons or rockets.

Rocket observations some 20 years ago showed rather surprisingly that the sun emits X radiation, amounting in total





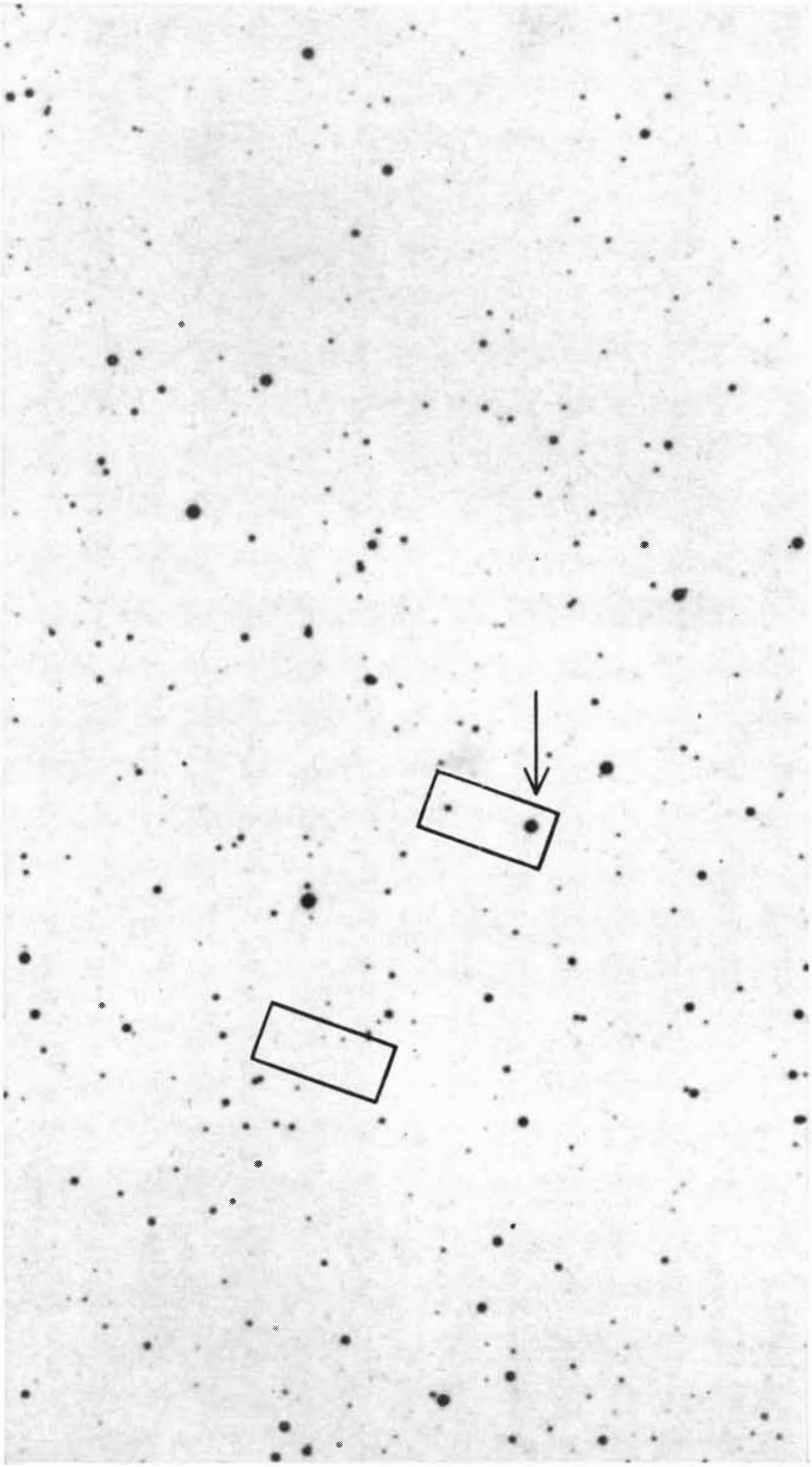
NEAREST X-RAY EMITTER is the sun. The X-ray image at the left was made during a rocket flight from the White Sands Missile Range on March 17, 1965. The image is the result of a 100-second exposure at a wavelength of two to 20 angstrom units, using an X-ray telescope built by the author and his associates at American Science and Engineering, Inc. The picture at the right shows the sun as photographed almost simultaneously in the light of alpha hydrogen (wavelength 6,564 angstroms) at the Sacramento Peak Observatory. The bright region at the upper right on the sun's disk coincides with the region of intense X-ray emission. The corona is also a strong source of X rays. If the sun were at the distance of the next nearest star, its X-ray emission could not be detected with present instruments. The Goddard Space Flight Center collaborated with American Science and Engineering on this experiment.

energy to about a millionth of the sun's output in the form of visible light. It was difficult to understand how the sun could generate X rays, which photon for photon are about 1,000 times more energetic than visible light. Moreover, the discovery immediately aroused curiosity about whether other stars also were X-ray emitters.

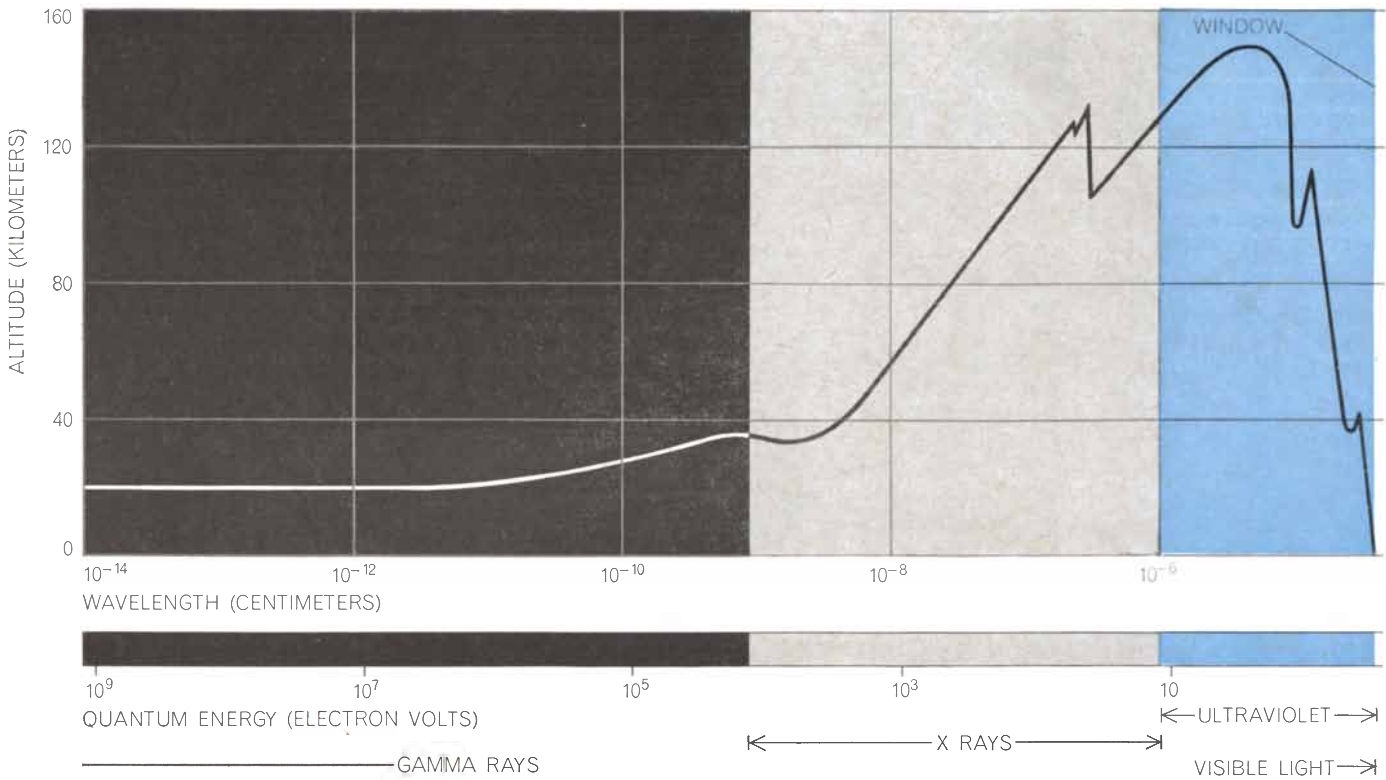
As rocket flights and opportunities to send up instrumented payloads became more frequent, Bruno B. Rossi of the Massachusetts Institute of Technology suggested an X-ray survey of the sky, and a group of us at American Science and Engineering, Inc., undertook the study. If other stars emitted no more X radiation than the sun did, it seemed doubtful that we could detect their X-ray emission with existing instruments. For example, if the sun were located at the distance of the nearest star, which is about four light-years away, the flux of its X-ray emission received at the earth would be reduced by a factor of about a billion. We hoped, however, that we might detect X rays from the moon that were generated by fluorescence due to the impact of X rays from the sun. And eventually from these tests we might obtain information enabling us to design instruments sensitive enough to search for X radiation from the stars.

The X-ray spectrum covers the range of wavelengths from a tenth of an angstrom to 100 angstroms. Our calculations indicated that X rays from distant sources could be detected only at very high energies, corresponding to wavelengths of 20 angstroms or less. In general, however, the higher the energy, the smaller the number of photons that can be expected to be emitted by an astronomical source. This meant that our detectors would have to be sensitive enough to detect and count a small number of X-ray photons. The proposed experiments therefore called for Geiger counters or scintillation counters; we chose Geiger counters for the first experiments. The detection apparatus we installed in the rocket was 100 to 1,000 times more sensitive to X rays than any that had been flown previously.

The instrumented Aerobee rocket was launched at the White Sands Missile Range at midnight on June 18, 1962. Our experiment had been prepared by Herbert Gursky, F. R. Paolini and me, with Rossi's collaboration. Some time before the rocket arrived at its peak altitude 225 kilometers (140 miles) above the earth's surface, doors opened to expose the detectors. With the rocket spinning



X-RAY SOURCE IN SCORPIO (*arrow*), **one of the most powerful X-ray emitters, is the first to be identified as a visible star. Named Sco X-1, the 13th-magnitude star lies within one of two rectangular areas deduced from rocket data to enclose the two most probable positions. Of several stars in the two rectangles, Sco X-1 was deemed to be the actual X-ray source because it is starlike, because its magnitude satisfies theoretical expectations and because its spectrum is richer in ultraviolet radiation than that of the average star. The tentative optical identification was made jointly by workers at the Tokyo Astronomical Observatory and the Mount Wilson and Palomar Observatories, using the rocket observations carried out jointly by the author's group and a group at the Massachusetts Institute of Technology. The finding photograph is from the collection of Palomar Sky Survey prints.**

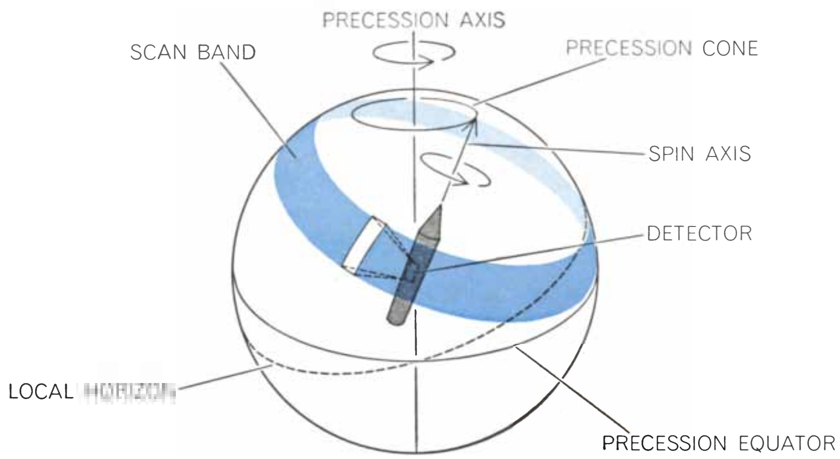


OPACITY OF EARTH'S ATMOSPHERE to incoming radiation is conveniently demonstrated by a highly irregular curve that indicates the altitude where electromagnetic radiation from space is reduced to half its intensity. The curve rises steeply at wavelengths corresponding to those of X rays and reaches a peak in the ultraviolet. A precipitous drop marks the opening of the narrow "window"

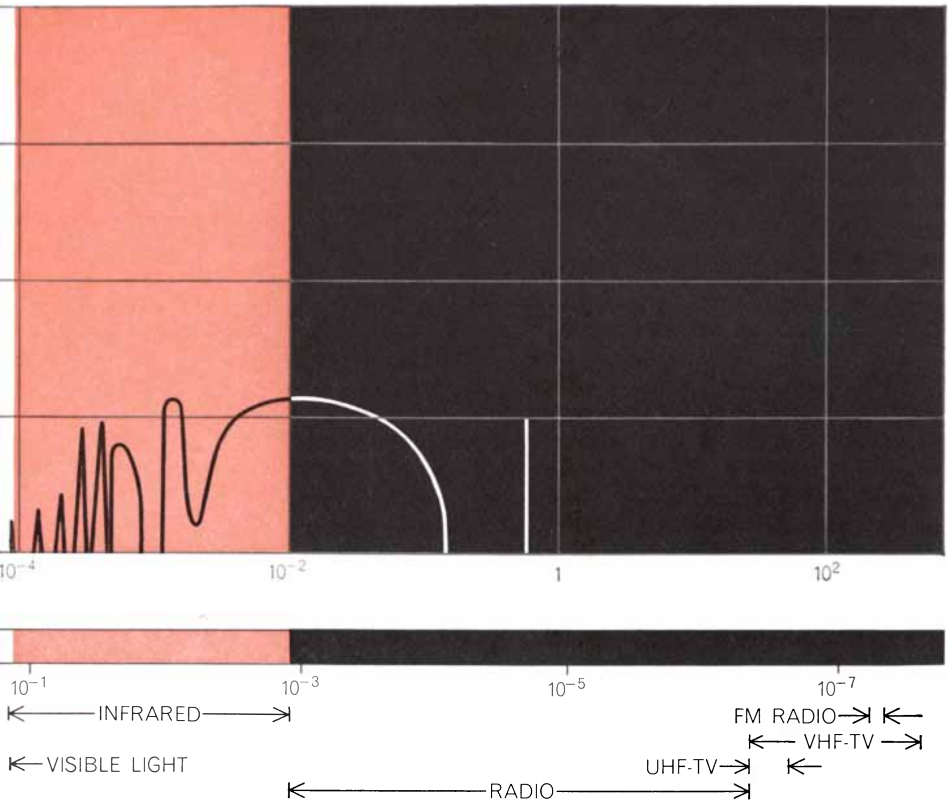
on its axis, the detectors scanned a 120-degree belt of the sky, including the position of the moon [*see bottom illustrations on these two pages*].

The telemeter signals from the detectors showed no indication of any X radiation coming from the moon. From the direction of the constellation Scorpio in the southern sky, however, the detectors revealed the presence of an intense source of X rays. The intensity registered by the counters was a million times greater than one would expect (on the basis of the sun's rate of X-ray emission) to arrive from any distant cosmic source!

Three months of close study of the records verified that the radiation was indeed X rays (two to eight angstroms in wavelength), that it came from outside the solar system and that the source was roughly in the direction of the center of our galaxy. What kind of object could be emitting such a powerful flux of X rays? The first surmise was that perhaps the observed radiation was coming not from a single object but from thousands of stars in the dense region at the galactic center. A simple calculation showed, however, that even such a large collection of stars, emitting X rays at the same rate as our sun, could not account for the observed amount of X radiation. Other explanations were proposed. The center of the galaxy is known to be generating a strong flux of radio waves, produced by the "synchrotron" process, in which radiation is emitted by energetic electrons spiraling along lines of magnetic force. The same process, involving much more energetic electrons, might give rise to X radiation. Further observations, however, threw some doubt on this explanation. We made two additional rocket surveys at different times of the year (in October, 1962, and June, 1963) that narrowed down the location of the strong X-ray source by triangulation, and we found that it was not actually in the galactic center. Meanwhile



X-RAY ROCKET ASTRONOMY requires techniques for establishing precisely where the detecting instruments are pointed at all times. The rocket is shown here at the center of a celestial sphere, with the X-ray detector scanning the sky at right angles to the flight path.

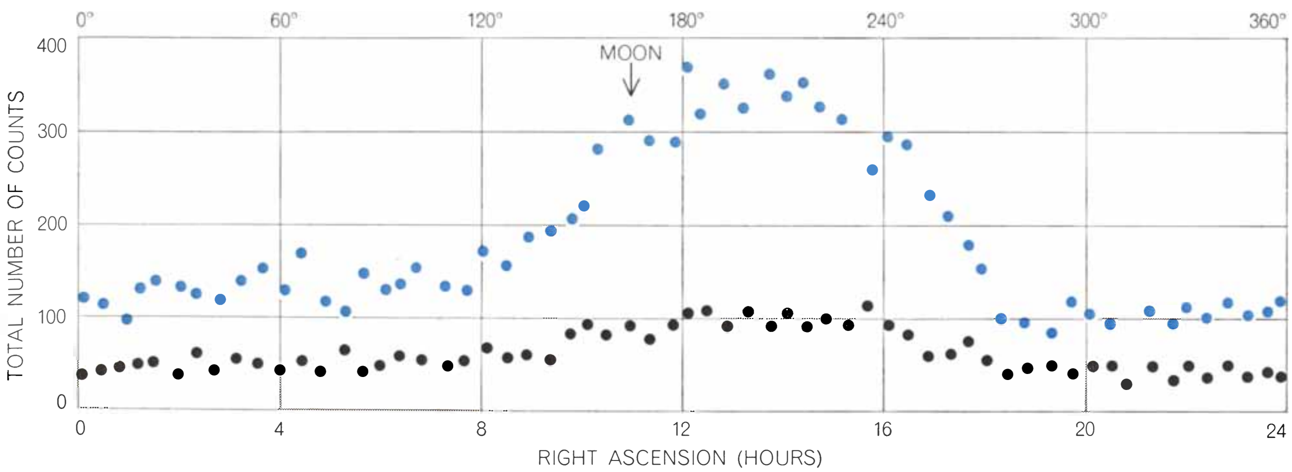


that lets in visible light. To carry out X-ray astronomy efficiently instruments must be lifted to an altitude of a few hundred kilometers. The X-ray spectrum covers the range of wavelengths from a tenth of an angstrom to 100 angstroms (10^{-9} to 10^{-6} centimeter).

Herbert Friedman and his collaborators at the Naval Research Laboratory succeeded in locating the position of the source within a two-degree arc in the sky, which suggested that the X-ray emitter was a single star rather than a large collection of them [see "X-Ray Astronomy," by Herbert Friedman; SCIENTIFIC AMERICAN, June, 1964].

By this time the evidence that the source was a discrete object had become so strong that we named it Sco (for Scorpius) X-1. One might have expected that an object pouring out so much energy in X radiation would be distinctly visible as at least a rather bright star. The region of the source was barren, however, of conspicuous stars. Several investigators therefore suggested that the X-ray emitter might be a neutron star, that is, a dying star that had degenerated to a gas of neutrons and faded from visibility. In such a star the matter would be packed to extraordinary density; if our sun, for example, were in that state, it would be compressed to a diameter of about 12 miles. The surface temperature of a neutron star might be 10 million degrees centigrade, compared with the sun's 6,000 degrees, and the emission from its surface could produce enough X radiation (one to 10 angstroms in wavelength) to be detectable at the earth. Very little of its emission would be in the form of light; its emission spectrum would essentially be limited to that of a Planckian black body.

Friedman's group at the Naval Research Laboratory conducted an experiment to test the neutron-star hypothesis. The experiment consisted in observing the X-ray source during its occultation, or eclipse, by the moon. If a small, sharply defined object such as a neutron star were responsible for the X-ray emission, the X radiation would disappear abruptly as the moon came between the source and the earth. This test could not be made on Sco X-1, because that object is not in a part of the sky where it can be occulted by the moon. Another strong X-ray source had been discovered, however, in our rocket surveys and that of the Naval Research Laboratory. This source lies in the Crab nebula, which is crossed by the moon at intervals of several years. Such an occultation occurred in July, 1964, and the Naval Research Laboratory arranged to have a rocket shot precisely timed to observe the event from the top of the earth's atmo-



FIRST OBSERVATION OF SCO X-1 was made from an Aerobee rocket on June 18, 1962. Colored dots represent counts made by a detector that passed both low-energy and high-energy X rays. Black dots show the response of a detector that passed only the more energetic X rays. The difference between the two curves shows that the emitting source produced predominantly low-energy X rays.

sphere just as the moon passed across the Crab. The observation showed that the X-ray source in the Crab extends over about one minute of arc. The wide extent of the source proved that it could not possibly be a neutron star [*see illustrations on opposite page*].

Our group followed this with two rocket observations of Sco X-1, which established that this object could not be a neutron star either. We made a detailed analysis of the spectrum of radiation from the Scorpio source by means of scintillation counters and Geiger counters with variable filters. The analysis showed that the Sco X-1 radiation was probably not confined to the black-body portion of the spectrum. Indeed, the data suggested that the source should be emitting light, and that its light emission was at least as strong as that of a faint visible star of the 13th magnitude.

This raised two possibilities. Sco X-1 might, like the Crab nebula, represent the remains of an exploded supernova, and the X radiation might be coming from a large cloud of hot gas, as appeared to be the case with the Crab. In that event the source might be too diffuse to be visible. The fact is that optical telescopes show no bright nebulosity in the Scorpio region. The other possibility was that Sco X-1 might actually be a faint star or at least a concentrated cloud less than two minutes of arc across, which would certainly be visible.

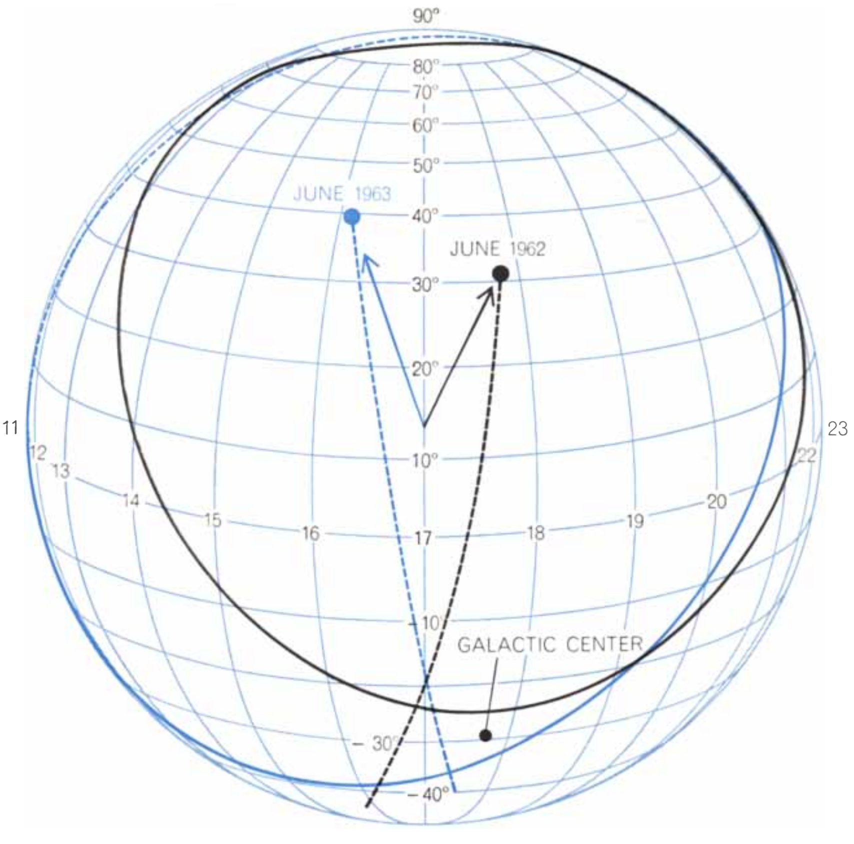
In collaboration with a group of investigators at M.I.T. we undertook to resolve Sco X-1 more precisely, seeking to determine if its size was less than two minutes of arc across. On March 8, 1966, we sent up a rocket with instruments designed to scan the object and collimate its X rays into narrow bands [*see illustrations on pages 42 and 44*]. The results of this inspection gave us a conclusive answer: it turned out that Sco X-1 was no larger than 20 seconds of arc across. This meant that the X-ray source must be visible as a star of at least the 13th magnitude.

The problem then was to identify the X-ray star among the visible stars at the indicated location. The position of Sco X-1 was known only within about one degree, and in its region of the sky there are about 100 13th-magnitude stars in each square degree. A detailed analysis of the new data was made to pinpoint the position more closely. This analysis narrowed the location to two equally probable positions where the star might be found. One was at right ascension 16 hours 17 minutes seven seconds plus or minus four seconds and declination minus 15 degrees 30 minutes 54 seconds plus or minus 30 seconds. The other position was at right ascension 16 hours 17 minutes 19 seconds plus or minus 30 seconds and declination minus 15 degrees 35 minutes 20 seconds plus or minus 30 seconds. The combined area of uncertainty was only about a thousandth of a square degree.

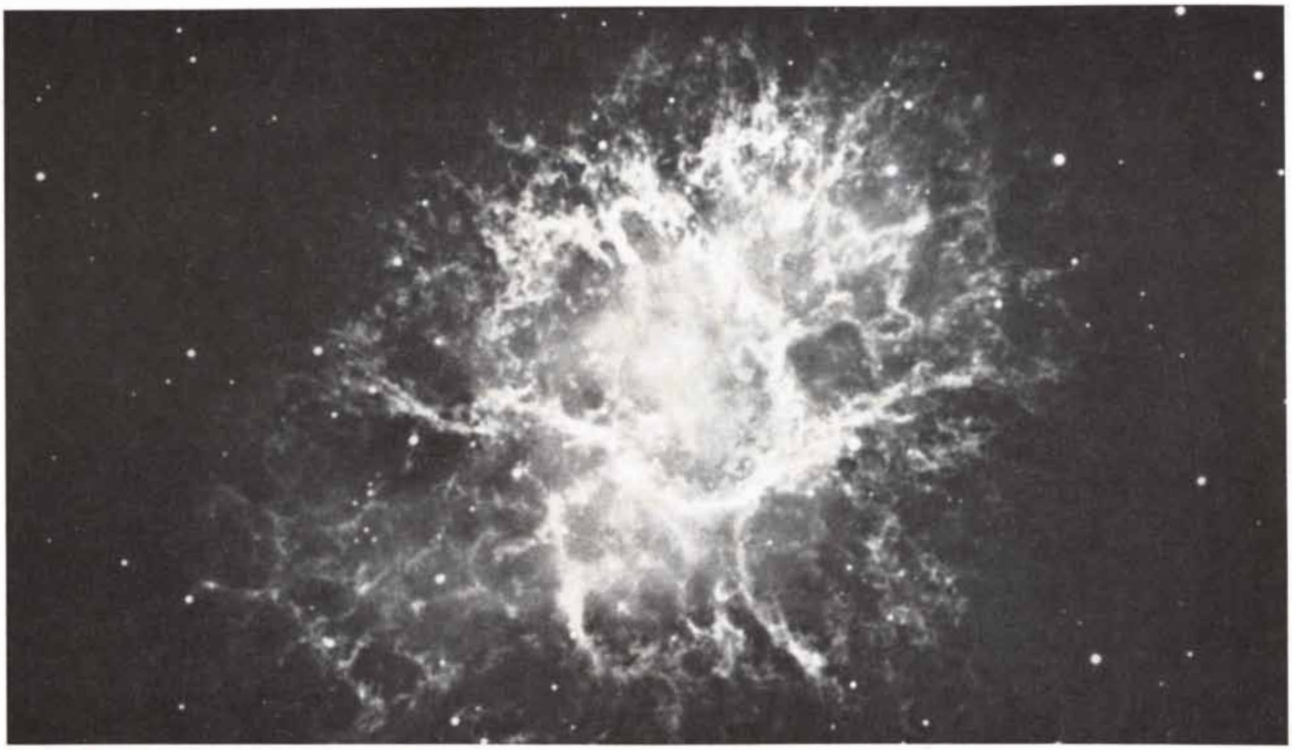
Given these positions, the Tokyo Astronomical Observatory and the Mount Wilson and Palomar Observatories made a telescopic search for Sco X-1. The Tokyo astronomers found the X-ray star immediately, and within a week the Palomar observers confirmed the identification [*see illustration on page 37*]. The visible star corresponding to the description of Sco X-1 from X-ray data was determined to be a 13th-magnitude star at right ascension 16 hours 17 minutes 4.3 seconds and declination minus 15 degrees 31 minutes 13 seconds—well within the area of uncertainty. It proved to be a blue star, as the X-ray-based studies had predicted. It also turned out to be a variable star, fluctuating in brightness by as much as a magnitude in a day. Its spectra showed emission lines of hydrogen and ionized helium and excitation lines of carbon, nitrogen and oxygen; an absorption line also showed the presence of calcium [*see top illustration on page 45*]. The absorption of the calcium light in interstellar space and the star's fixed position (that is, the absence of visible motion across the line of sight) indicate that the star is about 1,000 light-years from the earth.

Now that Sco X-1 can be examined with optical telescopes, it is beginning to yield some striking new information. The most provocative fact is that this star emits 1,000 times more energy in X rays than in visible light, a situation astronomers had never anticipated from their studies of the many varieties of known stars. There are indications that the X-ray emission of Sco X-1 is equal to the total energy output of the sun at all wavelengths.

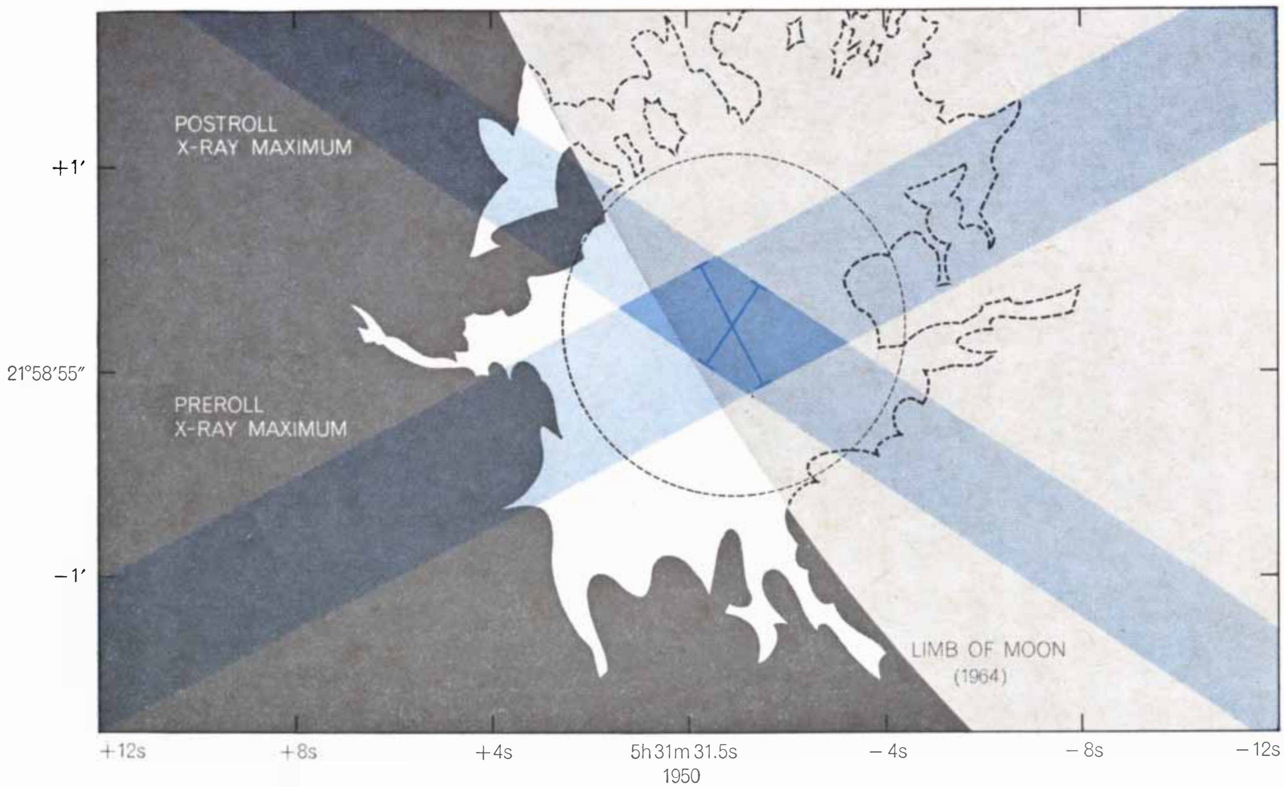
How can one explain such an enormous output of X rays? Rossi has suggested a hypothesis that has won much



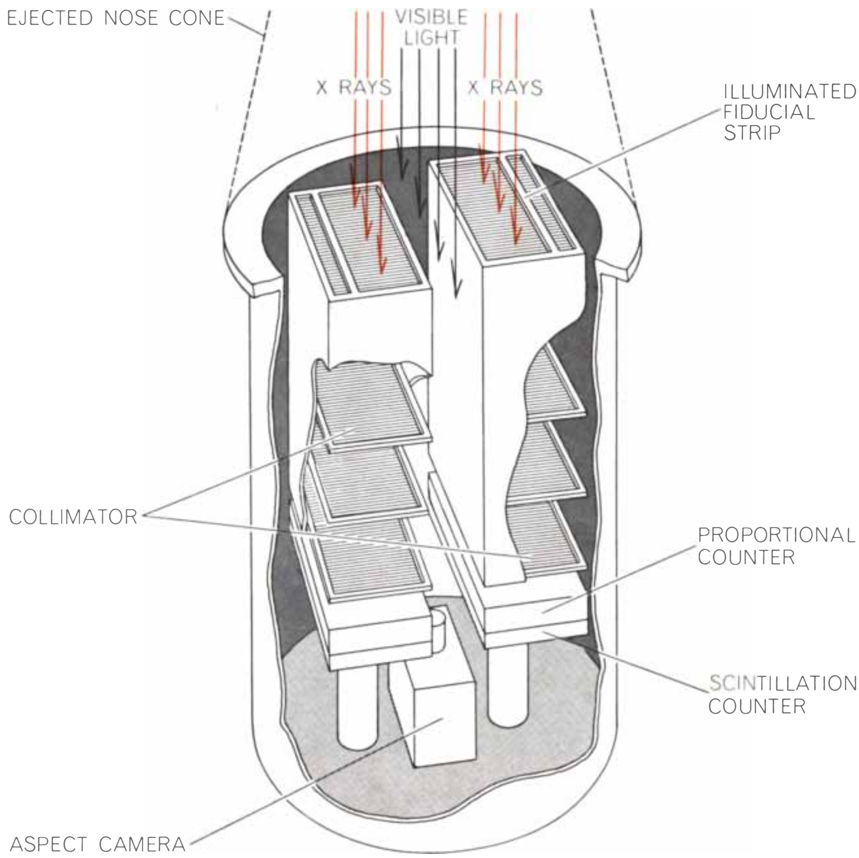
ANOTHER OBSERVATION OF SCO X-1 was made in June, 1963, with an X-ray detector that scanned the region of the sky shown by the colored curve. The detector flown a year earlier had scanned the region shown by the black curve. Arrows show how the two rockets were aimed when they left the earth. The directions of maximum X-ray intensity on the two flights define an intersection that roughly fixes the location of the X-ray source.



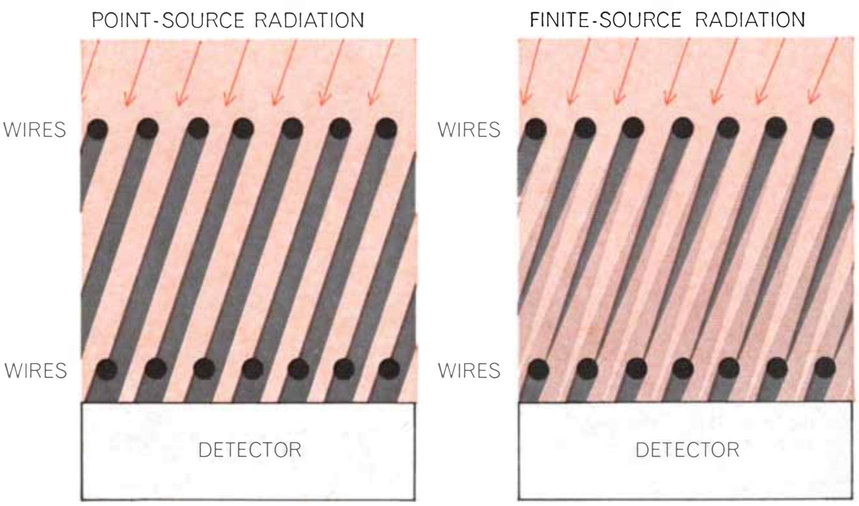
X-RAY SOURCE IN CRAB NEBULA, shown here in a photograph made in red light with the 200-inch telescope on Palomar Mountain, was observed as early as October, 1962, by the author and his colleagues. Although it was first thought that the X rays were coming from a starlike source, it was later found that they originated in an extended area in the central region of the nebula *(see below).*



LOCATION OF CRAB SOURCE was established in two ways. In July, 1964, when the moon passed in front of the nebula, a rocket observation was conducted by workers at the Naval Research Laboratory. They found that the X rays were not cut off abruptly by the moon, thereby proving that the radiation must originate from an extended source. In March, 1966, the author's group resurveyed the Crab source with a detector *(see illustrations on next page)* that resolved X radiation into a line. By rolling the rocket during the flight one could establish where the lines of maximum intensity crossed. The broken circle shows the approximate size of the source.



X-RAY DETECTOR used in pinpointing Sco X-1 employed two collimating systems, one about 5 percent longer than the other. Each collimator contains four banks of closely spaced wire screens. X rays entering the collimator are obstructed in varying degrees depending on their angle of entrance. Because the collimators differ in length, the amount of obscuration also differs for each angle. These differences show up in the X-ray counting rates and help to establish a unique direction for the X-ray source. The aspect camera records the star fields toward which the rocket is pointing, together with the pattern made by visible light that has filtered through the collimator screens. These visible-light patterns can be correlated with the star fields and X-ray counting rates to define possible locations of X-ray sources.



COLLIMATOR SYSTEM can differentiate between point sources of X rays and finite, or extended, sources. In the former case (*left*) the flux of radiation reaching the counter shows a sharp variation between maximum and minimum when the angle of the incoming radiation is shifted. When the source is an extended one (*right*), the variations are less pronounced.

support. He has proposed that the X radiation may be produced by a mechanism called *Bremsstrahlung:* the emission of radiation as the result of the "braking" of high-energy electrons by collision with positive ions. Theoretical calculations show that a comparatively small mass of hot gas (about a hundred-thousandth of the sun's mass) at a temperature in the vicinity of 50 million degrees C. could produce the X-ray output and the shape of the visual spectrum observed in Sco X-1.

This hypothesis, however, presents several difficulties. It is difficult to see how gravitation or a magnetic field could confine so hot a gas and prevent it from escaping into space. Moreover, the body would be expected to lose so much energy by radiation that it would cool to below the emission threshold within a few months or years unless it had an internal source of energy to maintain the high temperature. It is not clear how this continuous supply of energy would be generated in the gas or how it would be converted into heat. Sco X-1 is at least 80 years old as a visible star, according to available photographs of this region made in the past.

At least two other hypotheses are under study. Oscar Manley of our laboratory has suggested that Sco X-1 may be a star in the process of formation, and that its X radiation may be generated by synchrotron emission of the energetic electrons in the condensing cloud of hot gas. Iosif S. Shklovskii of the U.S.S.R. has proposed that the X-ray stars may be double-star systems that generate X rays through an interaction between the two partners. Consider a pair consisting of a large star of low density and a small, dense partner. The large star, during flares or surface explosions, may throw off masses of material that come within the effective gravitational field of the dense partner and fall into it; in so doing the electrons of the plunging gas may be accelerated to very high energies so that they produce X rays on colliding with ions in the dense star. One hopes that information bearing on these hypotheses will be obtained, and that perhaps new ideas will emerge, as more detailed studies and measurements are made on the radiations from the X-ray stars, particularly on possible correlations between the emission of visible light and X radiation.

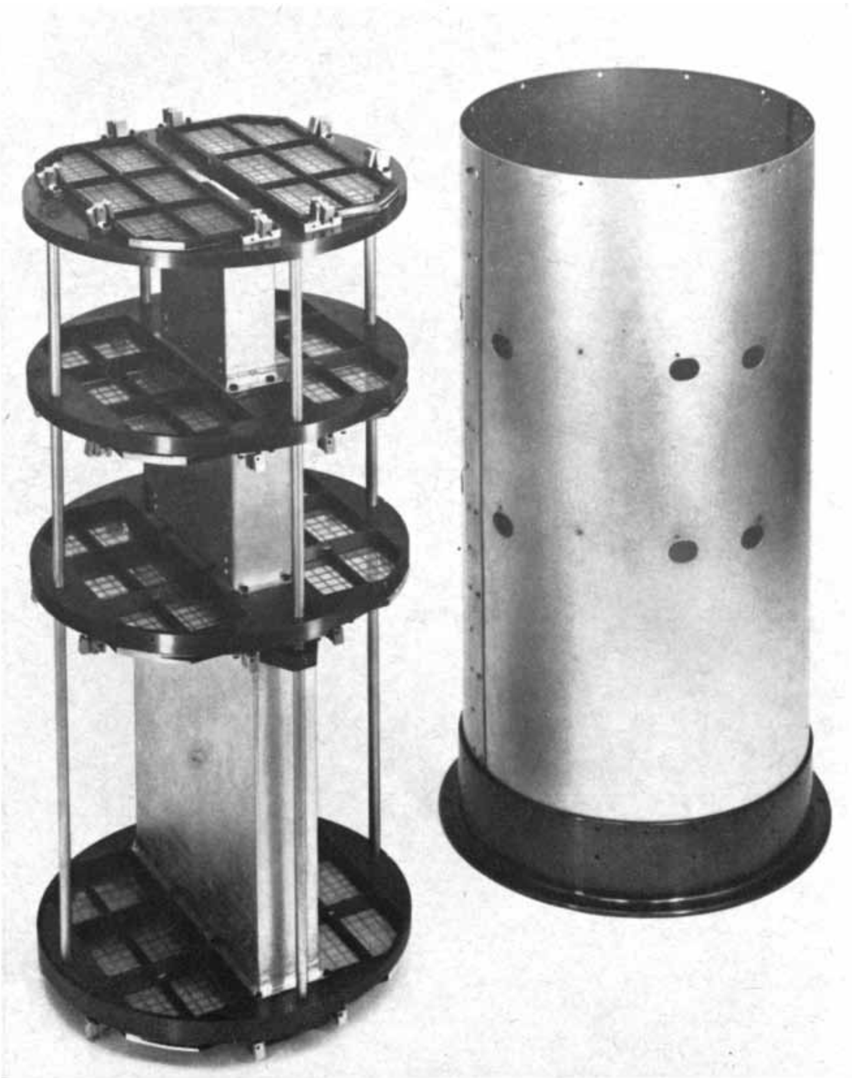
In the five years since Sco X-1 was discovered a total of about 30 X-ray stars, or at least sources of X radiation, have been detected in rocket surveys by the groups of investigators around the world who have joined in this search. A general, diffuse background of X rays in space has also been observed. About a dozen rockets have been flown on these missions, and the total observing time so far adds up to only one hour (five minutes being available in each flight). Nonetheless, a considerable amount of information has already been gained through the new window.

Only Sco X-1 and the source in the Crab nebula have been positively identified with visible objects. A third object apparently has been located with reasonable reliability. This source, in the constellation Cygnus, is called Cyg X-2. Allan R. Sandage of the Mount Wilson and Palomar Observatories was able to find a visible star in its approximate location that radiates strongly in the ultraviolet and is similar in optical characteristics to Sco X-1. Cyg X-2 is only about a twentieth as strong in X rays and visible light as Sco X-1, but it has several striking similarities to the latter, including fluctuations of its light emission.

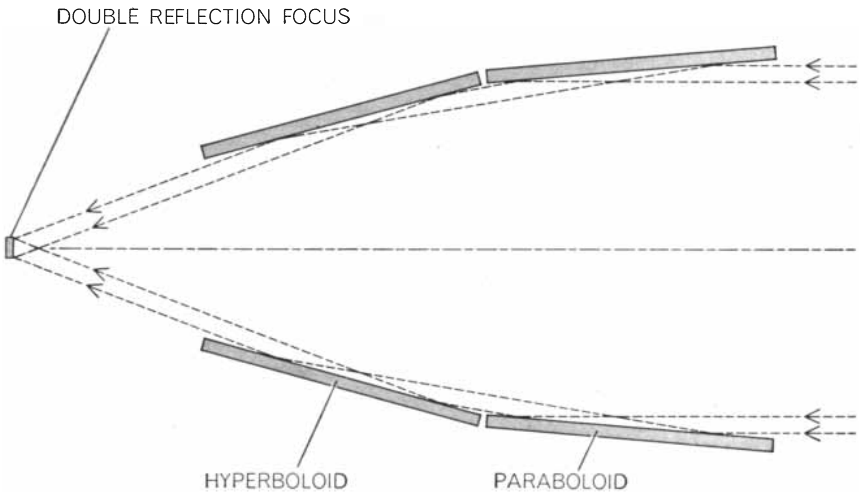
Three other sources have been tentatively identified by Friedman's group at the Naval Research Laboratory. These are Cas A (in Cassiopeia) and SN 1572, both of which are believed to be remnants of supernovas, and M 87, a strong emitter of radio waves outside our galaxy. In the same survey in which our group discovered Cyg X-2 we also found three other X-ray sources in Cygnus (Cyg X-1, Cyg X-3 and Cyg X-4) whose positions we have now located within minutes of arc but that have not yet been connected with visible stars. The 20 or so other X-ray sources that have been found, all within our galaxy, have not been located with precision.

Surveying the locations of all these X-ray emitters, one is struck by the fact that their distribution seems to coincide fairly well with that of the young stars and hydrogen clouds (the birthplaces of stars) in our galaxy [*see bottom illustration on page 45*]. It appears that most of the X-ray stars are located in the spiral arms of the galaxy. It is also notable that the X-ray stars vary greatly in intensity and in their spectral characteristics; for example, the X-ray emission of the weakest source found so far is only about a hundredth that of Sco X-1. In all probability the distribution of these stars and their variability will eventually give us important information about stellar evolution.

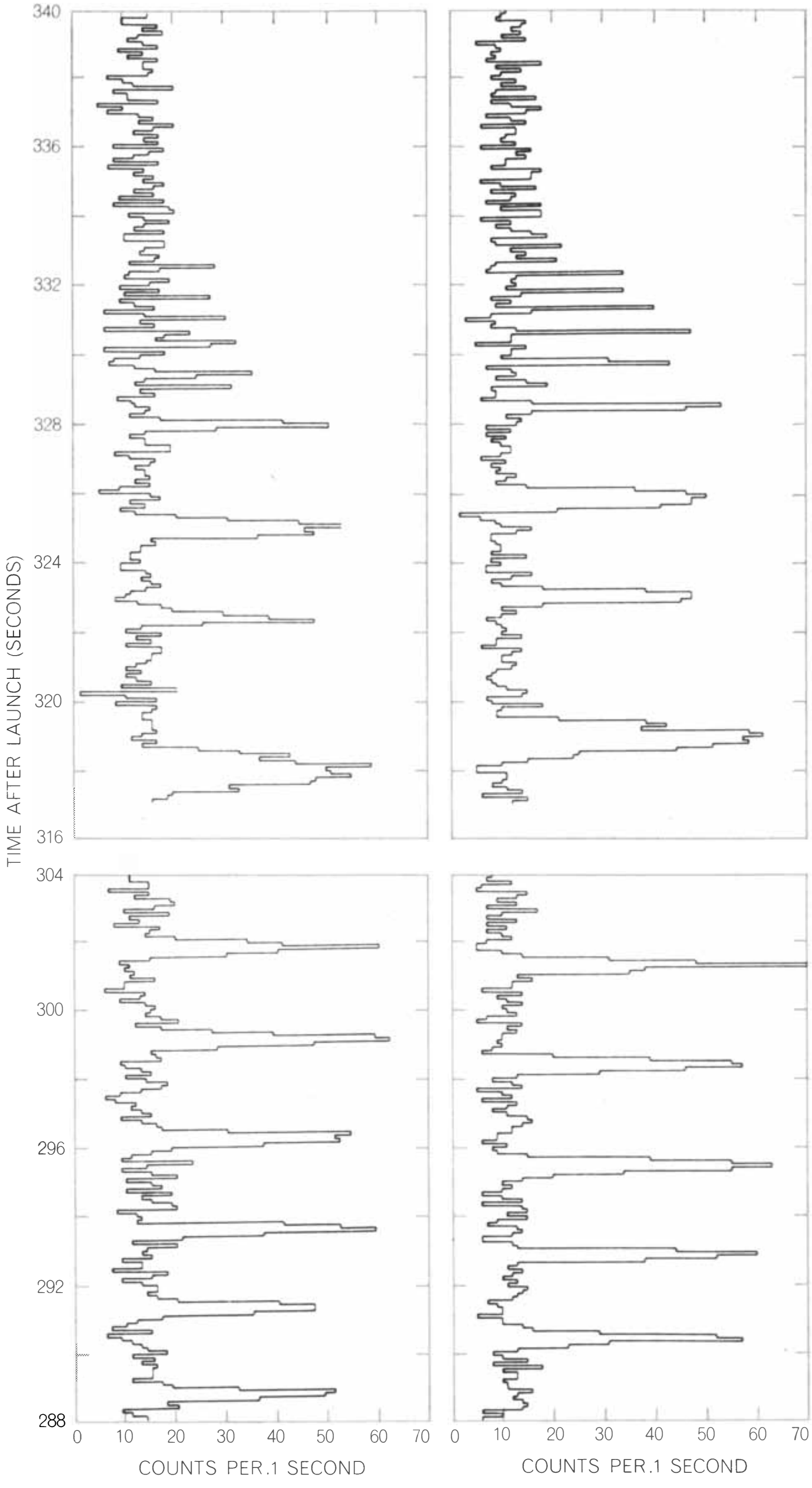
We know that both the birth and the death of stars must involve tremendous outputs of energy—energies that can



INSTRUMENT PACKAGE designed for the Aerobee rocket by the author's group is about 30 inches long and 12 inches in diameter. The collimating system (*left*) is the one shown in the drawing at the top of the opposite page; here, however, the unit is shown upside down. Each screen contains about 1,000 wires spaced .01 inch apart. The housing is at right.



FOCUSING X-RAY TELESCOPE exploits the fact that X rays behave like light rays if they strike surfaces at a low angle. In this telescope designed at American Science and Engineering X rays are focused by first glancing off a parabolic surface and then off a hyperbolic one.



DETECTOR VIEW OF SCO X-1 is coded in these histograms showing the accumulated X-ray counts per tenth of a second while the Aerobee rocket, fired on March 8, 1966, was pointed toward the X-ray source. Each peak coincides with a transit of the source across one of the transmission bands of one collimator. Because the collimators are different lengths (the longer one is on the left) the peaks do not quite line up. The displacement of the peaks defines a series of bands separated by about 1 degree 40 minutes on which the source must lie. The detectors were sensitive to X rays in the energy range from 1,000 to 24,000 electron volts.

readily generate the kind of short-wavelength radiation represented by X rays. As we gain some insight into the nature of this generating process we may be able to learn more about the evolution of stars from the X-ray stars than we can from normal, well-behaved stars.

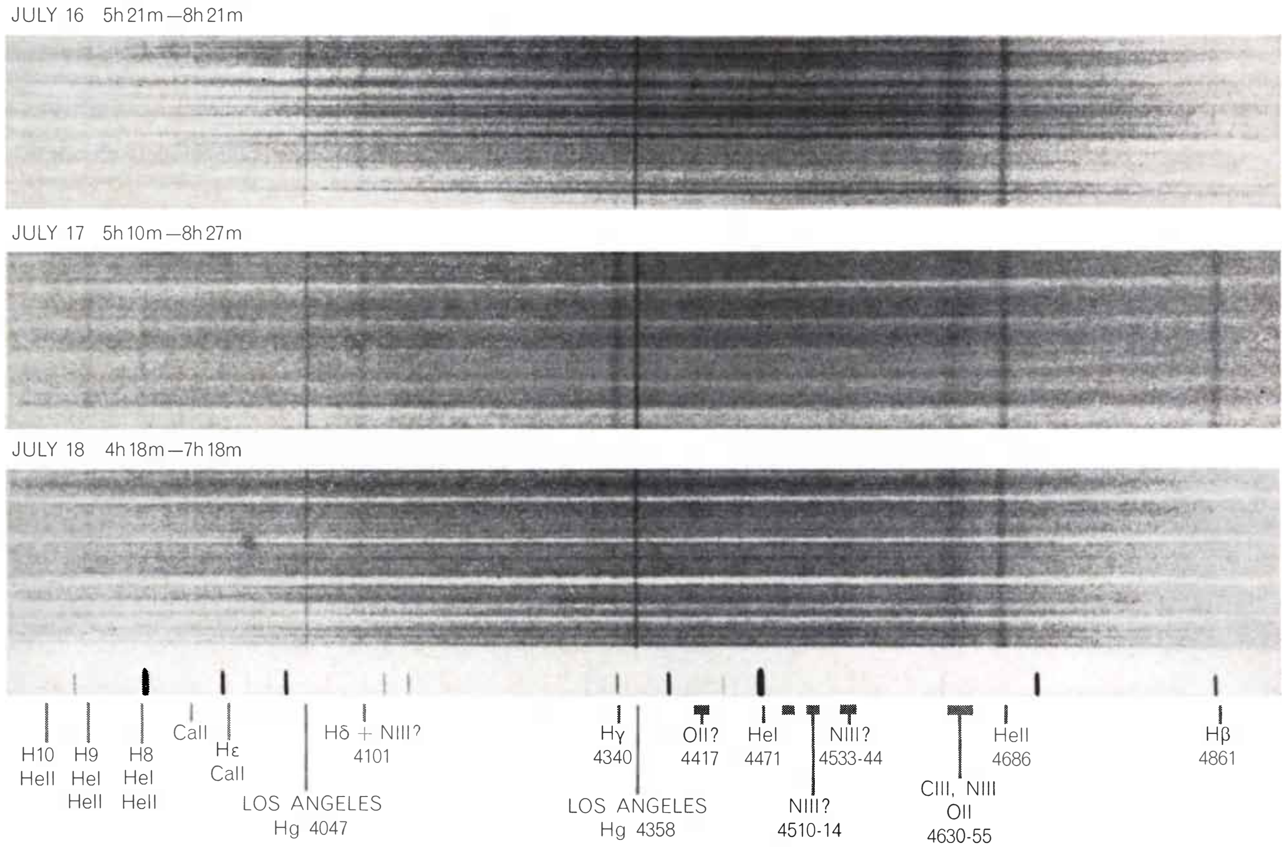
Progress in X-ray astronomy is proceeding at a rapid pace. The accuracy of resolution and measurement has increased many thousandfold within four years; with present techniques it is possible to locate the position of an X-ray star within four minutes of arc and to determine the size of X-ray objects as small as 20 seconds of arc.

All the sources we have studied so far are new types of objects, completely unknown before the rocket observations began. We have not yet been able to observe the X-ray emission of normal stars, nor can we yet detect the X radiation from galaxies such as M 31 in Andromeda, the nearest spiral galaxy resembling our own. In order to observe the X-ray emission of ordinary stars and galaxies the sensitivity of detectors must be improved a thousand times or more.

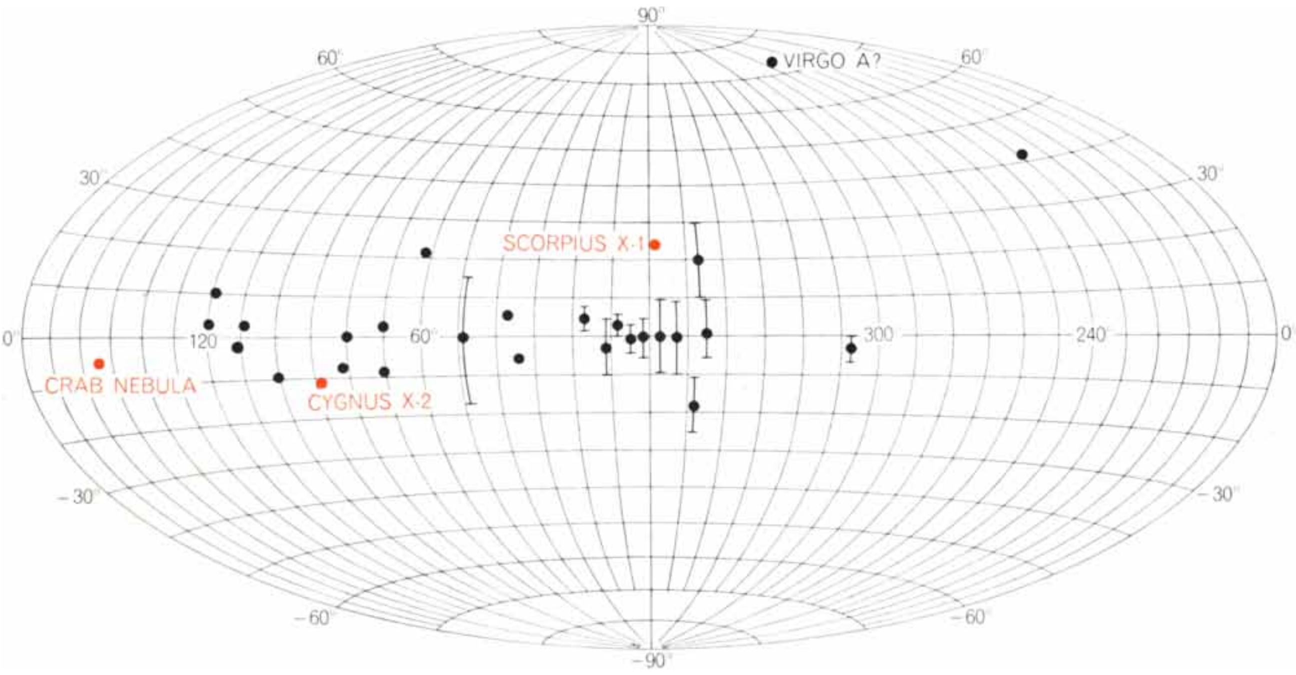
Technical means and devices that are just over the horizon will soon enable us to study the X-ray stars in much greater detail. For one thing, before long the instruments will be installed in satellites rather than in short-lived rockets, which will make possible observations extending over six months or more instead of only five minutes. Indeed, the day is probably not far off when we shall have X-ray telescopes scanning the sky from permanent orbits above the atmosphere.

Our laboratory has been working on the development of X-ray telescopes since 1960. The project is based on the finding that, notwithstanding the extreme shortness of X-ray waves, they can be collected and focused if they strike a suitable reflector at a small enough grazing angle [*see bottom illustration on preceding page*]. Applying this principle, we built a small X-ray telescope that in 1965 made X-ray pictures of the sun. The instrument was three inches in diameter, had a collecting area of less than one square centimeter and was able to resolve objects with a width of about half a minute of arc [*see illustration at left on page 36*].

Since then larger X-ray telescopes, capable of considerably finer resolution, have been built. The present versions are about 12 inches in diameter, have 50 square centimeters of collecting area and provide an angular resolution of about one second of arc. This approaches the



SPECTRA OF SCO X-1 were made on three successive nights, July 16, 17 and 18, 1966, by Allan R. Sandage, who used the 200-inch telescope on Palomar Mountain. The overall magnitude of the star tentatively identified as Sco X-1 was 12.6, 13.4 and 12.6 on the three nights. It can be seen that the night-to-night variation at certain wavelengths, particularly the hydrogen (*H*) emission lines, was even more pronounced. The identification of the lines is tentative; those marked "Los Angeles" are emission lines from streetlights.

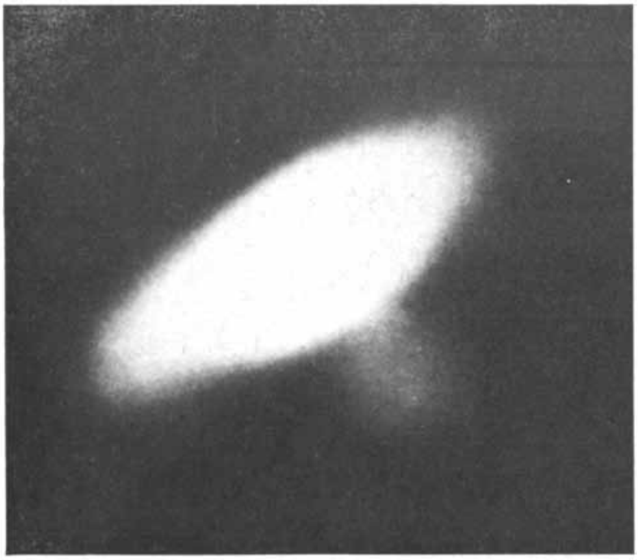


DISTRIBUTION OF X-RAY SOURCES correlates strongly with the equator of the galaxy, which divides this map horizontally. The center of the map represents the direction of the center of the galaxy. Error bars are shown for sources whose position is not yet precisely determined. Only three sources have been identified with optically visible objects: the Crab source, Sco X-1 and Cyg X-2.

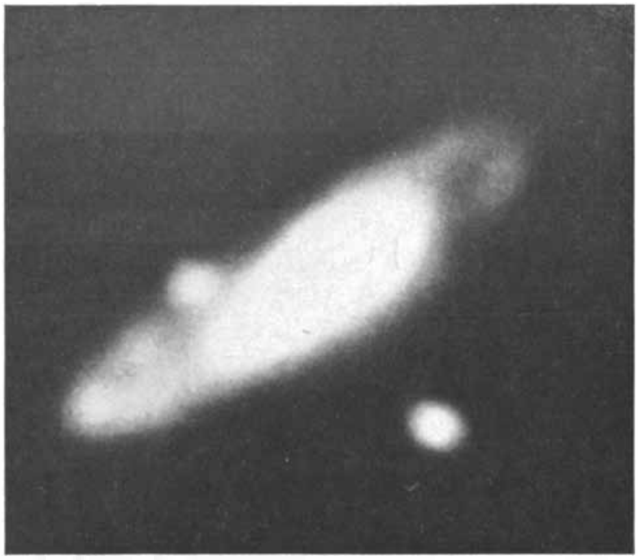
best that can be achieved with ground-based optical telescopes. Atmospheric turbulence limits their resolution to about .3 second of arc. In principle, because ultimate resolution is a function of wavelength, X-ray optics could produce images 500 times sharper than visible-light optics.

With instruments now available it will be possible, given enough observing time, to locate X-ray stars within a second of arc and to make a detailed study of the structure of sources that extend over a wider span. We are now building an X-ray telescope that will incorporate a spectrograph; this will make it possible to analyze the spectra of X-ray sources in detail, to record specific emission and absorption lines and shifts of these lines, in short, to obtain the kinds of information an optical telescope provides. The instrument is scheduled to be flown in an Apollo space shot in late 1968, and it will be aimed to make a detailed study of the flares on the sun.

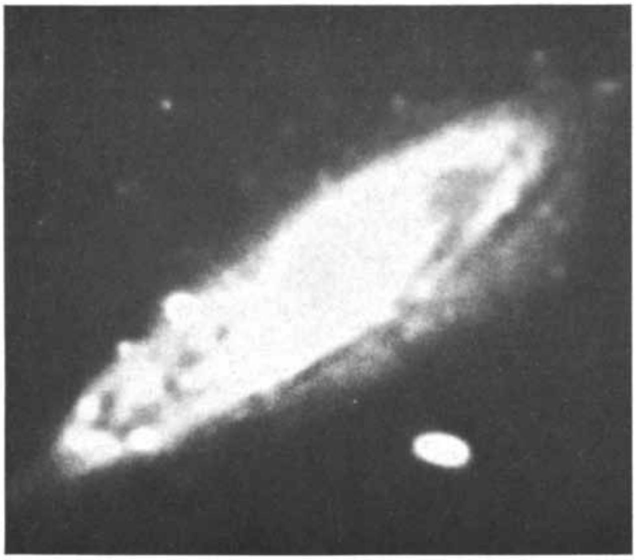
Plans are already under study for sending up, within a few years, orbiting observatories that will carry larger X-ray telescopes (up to 10 feet in diameter and with a focal length of 100 feet) and that will make X-ray explorations of the entire sky. There is every reason to believe the X-ray telescope will be able to produce high-quality pictures as detailed and as rich in information as those now produced by optical telescopes. One looks forward with eager anticipation to what a clear view of the X-ray universe may reveal.



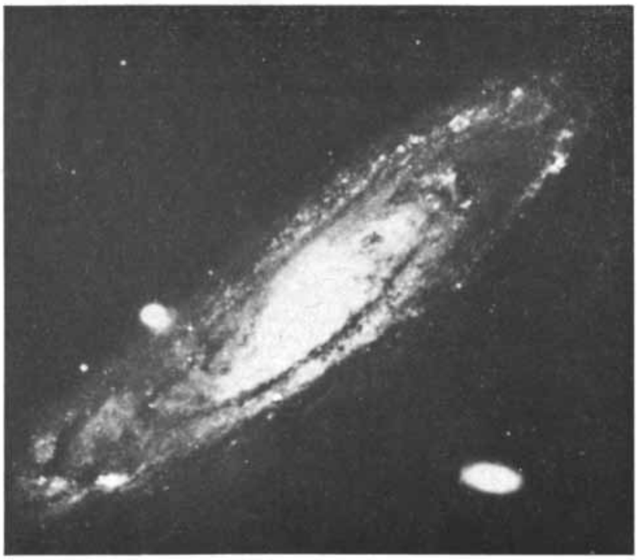
34 ARC MINUTES



12 ARC MINUTES



1 ARC MINUTE



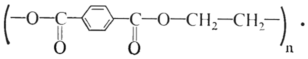
1 ARC SECOND

EFFECT OF IMPROVING TELESCOPE RESOLUTION is demonstrated with four views of the great galaxy in Andromeda, M 31, of which three are severely out of focus. They demonstrate how the galaxy would look if photographed with instruments of low resolution, comparable to some of those used in the early development of X-ray astronomy. The illustration is taken from a report published by the National Academy of Sciences. The X-ray view of the sun on page 36 was made with a telescope whose resolving power was about 45 arc seconds. The Sco X-1 detectors had an effective resolution of 20 arc seconds. The highest resolution yet achieved in X-ray optics is about 1 arc second. Ground-based optical telescopes, under good seeing conditions, have a resolution of about .3 arc second.

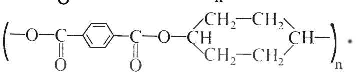
The hope of doing each other some good prompts these advertisements

Carpeting power

As a practical holiday gift for the family, consider carpet. This was the year that 100% polyester carpeting won acceptance. The particular polyester to ask for is KODEL II. All other polyester fibers of commerce (including others trademarked KODEL) are poly(ethylene terephthalate), to wit,



This one is



One would expect much different properties, and one would be right.

The ring of methylenes drops the density of the polymer from 1.38 to 1.22. This means you buy less dead weight and more carpeting power with your money.

Specific gravity of the polymer accounts for but part of the difference. Melting point rises from 250 to 290 C. Elongation at break drops from 45-35% to 34-24%. The stress-strain characteristic curve changes. Strength in grams/denier drops from 5.5-4.5 to 2.5-3.0. (For monofilament fishline we wouldn't brag about the strength change, but for carpets it helps.) In concert the changes lead to fiber that remains through processing more like bundles of springs than rods. On the floor the advantage is quickly perceptible to the bare foot. Yet the added softness fails to prevent the fiber from springing back faster from shoe traffic and the pressure of an occupied chair.

For fire resistance, nonallergenicity, and easy cleaning and stain removal, poly(ethylene terephthalate) is probably just as good a fiber.

Be kind. Let the carpeting salesman make his pitch for KODEL II *Fiber even if he knows less about it than you now know. At least he can show you colors and textures and talk price.*

The colors of nature

It frightens us to see how some scientific workers use color photography. We have too much stake in it to let them go unwarned of where they are misplacing their confidence. That we are reputable and trustworthy they know, and they surmise that we claim our various systems of color photography record, retain, and precisely reproduce all the colors of the real world. *We make no such claim, nor does any other reputable photographic manufacturer.*

How thoroughly our color films and services *please* vast numbers of people is indicated in part by our financial statements over the years. How sensitive we can make our products to color *change* explains the great growth of technical color photography, still and motion picture. Otherwise, beware. Just to express what color a thing is—let alone reproducing the color—can be tough once past the level of precision of "oh, a sort of reddish tan."

Absolute methods do exist. They are highly objective, call for a spectrophotometer and some computer hardware and software, and are more feasible for paint manufacturers than for field biologists. Actually, words like "reddish tan" serve quite well, given a large enough lexicon of verbal designators coupled tightly to a set of reference samples.

Of several such systems available, one particularly favored in current literature is a book of color samples and names issued by Robert Ridgway of the Smithsonian Institution in 1912. Lucky and well funded is the scientist who can acquire an unravaged copy of Ridgway from a rare-book dealer. Yet many a current author is limiting his communication to readers and a posterity in possession of Ridgway.

Thanks to Marcel Locquin of the Muséum National d'Histoire Naturelle in Paris, it turns out we can help after all. Under the title "Chromotaxia," he publishes a book which comes with a set of KODAK Color Compensating Filters. We make these for professional photographers' use in creating (not recording!) the color balance that artistic intuition demands in a print. For scientists, Locquin has assembled a vocabulary and a technique for using combinations of two or three of these filters to match and designate any of a broad gamut of natural colors—*or Ridgway colors*—with the most elegant precision and no additional instruments. The filters are easy and inexpensive for frequent users to replace annually as recommended, because the photographic artists are helping with the economics.

M. Locquin informs us that his price for "Chromotaxia" is $40. His address is 14, Rue de Buffon, Paris (5^me^), France. Directions are in French and color names in French, English, German, and Latin. A certain official weight has been given the system. Locquin has deposited his master set of KODAK *Filters with the Bibliothèque Nationale and is relying on our spectrophotometric quality controls for uniformity. That kind of confidence frightens us less. One other point:* "Tous excitants (tabac, alcool, médicaments, musique violente, odeurs fortes) doivent être écartés. Ils déforment la courbe de réponse de l'œil."

Marcel Locquin et les filtres

The moon job

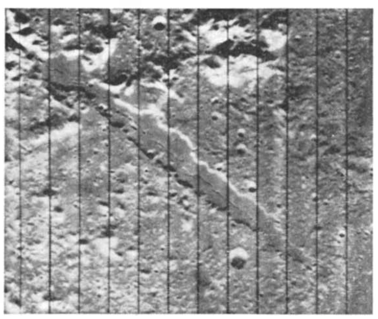
As expected of any Kodak photographic system, the five Lunar Orbiters and associated ground reconstruction equipment have done their job.

Now what was the good of it all?

The 35th President of the United States set a goal of planting an American foot on the moon. Voters remembered about Balboa's foot on the Pacific beach and Peary's at the North Pole. The project became comprehensible.

As an essential preliminary, the five Lunar Orbiters spelled out in full the choice of landing sites. The entire earthward face of the moon is now mapped in 10 to 100 times the detail of before. About the entire backside more detail is now recorded than about much of the staid old earth that man's foot has long trod.

With the needs of the men of action thus seen to, a handsome payoff was still left for the thoughtful side of the human spirit. The founders of civilization millenia ago considered the origin of the earth and moon an important subject. Enjoying easier times, we ought to consider it all the more worthy of attention.



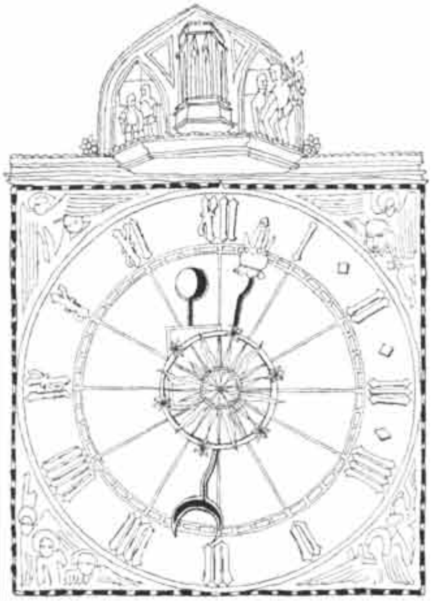
NASA Langley

- This sinuous lunar rill northeast of Mare Imbrium looks like a river. In this picture may be found evidence either for or against a flowing medium. Defenders of either view must wind up wiser about the structure of planetary bodies.
- Mounds our equipment photographed near the crater Marius require explanation.
- The photographs of the region of Aristarchus, where earlier observers at telescopes reported smoke or luminescence, may reveal signs of moonquakes, which would call for a moon capable of quaking.
- Hexagonal craters that appear in some of the photography suggest a three-way lunar substructure. A simpler explanation would be welcome.
- The absence of maria from the backside is obviously telling us something about the relation of the earth to the mechanism of mare formation. If obvious, what's the message?

One good from our lunar endeavors: those who set foot on the moon won't be bored for lack of things to investigate.

Kodak

SCIENCE AND



The Nobel Prizes

The Nobel prizes in science for 1967 were awarded for studies of the eye, for clarification of the energy sources of stars and for investigations of high-speed chemical reactions. The prize for physiology and medicine was shared by H. K. Hartline and George Wald of the U.S. and Ragnar Granit of Sweden "for their discoveries concerning the primary chemical and physiological visual processes in the eye." The prize in physics was awarded to Hans Bethe of Cornell University "for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production of stars." The prize for chemistry was shared by George Porter and R. G. W. Norrish of Britain and Manfred Eigen of Germany "for their studies of extremely fast chemical reactions."

A member of the Harvard University faculty since 1934, Wald has been concerned with the chemical events in the retina that underlie vision (see "Eye and Camera," by George Wald; SCIENTIFIC AMERICAN, August, 1950). In 1933, while still a postdoctoral fellow in Berlin and Zurich, he demonstrated that the eye contains vitamin A. He found that the vitamin appears when the light-sensitive pigment rhodopsin is bleached by light and disappears when rhodopsin is resynthesized during dark adaptation. Subsequently he found that rhodopsin consists of a colorless protein (opsin) that combines with a yellow carotenoid he called retinene. Other workers then showed that retinene is vitamin A from which two terminal hydrogen atoms have been removed. When light strikes rhodopsin, retinene is released and is converted to vitamin A. In the dark the vitamin A is converted to retinene, which then recombines with opsin to form rhodopsin.

Hartline and Granit have been concerned with the electrical impulses that are induced as a consequence of the chemical events in the retina. A faculty member of Rockefeller University, Hartline devised methods for recording the nerve impulses from single cells of the eye of the horseshoe crab and cold-blooded vertebrates. He and his associates were the first to demonstrate that, in his own words, "individual nerve cells [in the retina] never act independently; it is the integrated action of all units of the visual system that give rise to vision." For example, he found that the cells in the retina interact in such a way that they heighten the contrast at the edges of objects (see "How Cells Receive Stimuli," by William H. Miller, Floyd Ratliff and H. K. Hartline; SCIENTIFIC AMERICAN, September, 1961). Granit recently retired as director of the Neurophysiological Institute at the Royal Caroline Institute in Stockholm. His investigations have shown that the eye contains cells that are specifically sensitive to light of different wavelengths, thus confirming a theory of color vision that was first put forward by Thomas Young in 1800. Granit has also conducted extensive studies of the integrative action of the spinal cord.

Bethe joined the faculty of Cornell University in 1935 after leaving the University of Munich and teaching briefly in Britain. He has made important contributions to many areas of theoretical physics, including the theory of metals, meson theory and quantum electrodynamics. In particular, he is credited with synthesizing many of the ideas of nuclear physics that began to evolve in the early and middle 1930's. His studies of thermonuclear reactions in stars, cited by the Nobel committee, were a logical extension of this work. During World War II, Bethe was director of the theoretical physics division at Los Alamos, where the first atomic bomb was designed and built. At the same time he examined the theory and possibility of building a thermonuclear bomb, although he was later opposed to its construction (see "The Hydrogen Bomb: II," by Hans A. Bethe; SCIENTIFIC AMERICAN, April, 1950).

Norrish and Porter collaborated as teacher and protégé respectively at the University of Cambridge from 1949 until 1955, when Porter moved to the University of Sheffield. This past September, Porter was made director of the Royal Institution in London. The two physical chemists developed the technique of flash photolysis, in which simple chemical systems, in solution or in the gas phase, are subjected to a burst of light lasting about a microsecond. The energy so introduced gives rise to a high concentration of short-lived chemical species, which can be identified by spectroscopy. In this way Norrish and Porter identified a number of rare species whose existence had only been postulated.

Eigen, the youngest of the seven science prizewinners (he is 40), devised the "temperature jump" method for analyzing high-speed reactions. In this method a brief high-voltage pulse is used to upset the equilibrium of a chemical system, usually a system in solution, that has reached equilibrium. The results are also observed by spectroscopy. Now chairman of the Max Planck Institute for Physical Chemistry in Göttingen, Eigen has recently turned his attention to the high-speed behavior of enzyme systems.

Twinkling Galaxy

A new astronomical observation, just reported from the Mount Wilson and Palomar Observatories, lends strong support to the hypothesis that quasars, those starlike sources of intense radio energy, are among the most distant objects in the universe. Because the light from quasars is strongly shifted to the red end of the spectrum, like light from the most remote galaxies, one school of astronomers has consistently argued that quasars must be at "cosmological" distances. An opposing school, however, has used the evidence that many quasars show a rapid variation in light output to contend that they must be fairly small objects and therefore not very far away. If they were very distant, in addition to being very small and very bright, it would be difficult to account for their enormous rate of energy release.

The new finding, reported in *The Astrophysical Journal* in separate papers by J. B. Oke and Allan R. Sandage, is that the radio galaxy 3*C* 371, which is clearly galaxy-like and not starlike—and also indisputably distant—exhibits a variation in light output. The variation, first recorded by Oke, is about half a magnitude in a period of less than 24 hours. The observation was independently confirmed by Sandage in the course of using broadband photometry to monitor the class of galaxies to which 3*C* 371 belongs. Other galaxies of this class, known as *N* galaxies, have not shown a variation. "The optical variation of 3*C* 371 by at least .5 magnitude," Sandage writes, "provides the single counterexample needed to show that rapid variations of optical flux of any object does not require that the object be local."

The designation "*N*," which stands for nuclear, is applied to galaxies that somewhat resemble quasars in that most of their light comes from a pointlike nucleus. All *N* galaxies, however, show a nebulous outer envelope, whereas all quasars are indistinguishable from stars. Both quasars and *N*-type galaxies have intense emission lines and emit much more ultraviolet radiation than normal stars do. Still a third type of astronomical object, the Seyfert galaxy, resembles both quasars and *N*-type galaxies. Seyfert galaxies also have starlike nuclei, but nearly all of them show evidence of a spiral outer structure. In his paper Sandage concludes that "the case of 3*C* 371, combined with the probable connection between [quasars] and *N* galaxies through their optical appearance, similarity of radio properties, and now their light variation, would seem to constitute a strong argument for the cosmological interpretation of the redshift of quasars."

Rendezvous with Venus

Within a period of 37 hours in October two spacecraft, launched four months earlier, made a successful rendezvous with Venus. The first to arrive was the Russian craft *Venus 4,* which parachuted an insulated capsule through Venus' atmosphere. The following day (October 19) the American vehicle *Mariner 5* passed within 2,480 miles of the planet's surface. The Russian capsule provided the first direct observations of the planet's atmosphere and is reported to have reached the surface.

The capsule of *Venus 4* sent back a stream of information for 90 minutes after beginning its slow descent through the increasingly hot atmosphere. During this period the temperature rose from 40 degrees to 280 degrees centigrade (104 degrees to 536 degrees Fahrenheit). The composition of the atmosphere was 90 to 95 percent carbon dioxide, with no more than 1.5 percent oxygen and water vapor. Nitrogen was reported to be less than 7 percent. It had been assumed previously that nitrogen made up a large fraction of Venus' atmosphere. The density of the atmosphere was higher than expected: 15 to 22 times greater than the density of the terrestrial atmosphere. The Russian craft found no significant magnetic field, no radiation belts and only a weak hydrogen corona. *Venus 4* was the second Russian capsule to enter Venus' atmosphere and presumably crash into the planet's surface. *Venus 3* reached the planet on March 1, 1966, but failed to send back information.

Viewing Venus from a distance, *Mariner 5* generally confirmed the observations of *Venus 4,* insofar as the data could be compared. *Mariner 5* determined that Venus' magnetic field was less than 1/300th of the earth's and possibly zero. Its instruments also showed that the planet's radiation belts were weaker than the earth's by a factor of 10^5 or 10^6. Indirect measurements of Venus' atmosphere suggested that the carbon dioxide content was between 75 and 85 percent, with the balance undetermined. Unlike *Venus 4, Mariner 5* found evidence of a strong hydrogen corona. The conflict may be only apparent, however, because *Venus 4* made its descent on the dark side of the planet and *Mariner 5* made its observations on the sunny side.

Some of *Mariner 5*'s most precise results were those still being computed from the dynamics of its trajectory, as revealed by the Doppler shift in the craft's radio signals. For example, the earth-Venus distance will be computed with an error of less than 100 yards and the earth-sun distance (the astronomical unit) with an error of 100 kilometers. New values are also being derived for the relative masses of Venus, the earth, the moon and the sun.

The Russians have now sent 18 probes to Mars and Venus, compared with only five for the U.S. A number of American planetary probes planned for the near future have been eliminated by Congressional cuts in the budget of the National Aeronautics and Space Administration. Only four probes are now planned: two photographic flybys of Mars in 1969 and two efforts to land a capsule on Mars in 1975.

Poverty and Mental Retardation

A Duke University psychologist suggests that physically and mentally normal children can be transformed into retarded ones during the interval between their first and third birthdays. Since only one out of four mentally retarded individuals is handicapped as a consequence of known hereditary defects or other physical causes, 75 percent of retardation may thus be environmental in origin.

Analyzing the reports of several experimental preschool programs, Donald J. Stedman, research director of Duke University's Education Improvement Program in Durham, N.C., found that among children from deprived backgrounds nearly 80 percent scored as "borderline retardates" when tested at school-entrance age, compared with only 15 percent of children from all income levels. Stedman obtained the same low scores when he tested deprived Durham children between the ages of four and six. He next tested infants with similarly deprived backgrounds at the ages of one, three, six, nine, 12 and 15 months; their scores proved to be better than the national average.

Seeking out the specific environmental factors that may be responsible for retardation, Stedman points to studies in Mexico and elsewhere that show a correlation between malnutrition and intellectual underdevelopment. He believes that an effect of equal or greater importance is produced by an impoverished external environment on children from 12 to 36 months old. During these critical months, Stedman points out, the child's use of language accelerates, as does the associated intellectual experience of classifying in logical fashion the increasing number of things the child encounters in the surrounding world. Because the ability to classify depends on memory processes, tests of memory efficiency provide a sensitive measure of the child's intellectual growth. The children from deprived backgrounds enrolled in Duke's Education Improvement Program, Stedman reports, show a "horrendous" deficiency in this respect.

Stop-and-Go Continents

Continental drift, the slow movement of the continents over the surface of a slightly plastic earth, may be a


We'll take a mini credit
for the skirts.

stop-and-go affair, J. C. Briden of the University of Oxford has suggested in *Nature*. One line of evidence for continental drift comes from paleomagnetism: the record of the changing direction from a given part of the world to the earth's magnetic pole, frozen into rocks when they were formed. The present orientation of the rocks shows that they were formed in different latitudes at different times, suggesting the movement of the continents. The fact that in Europe and North America the indicated directions to the pole in each geologic period change in a regular way with the passage of geologic time has seemed to indicate that the drifting process, although extremely slow, must have been continuous.

Briden examined paleomagnetic data for Africa, South America, India and Antarctica, which are thought to have once formed a vast southern continent called Gondwanaland. When the data for these continents are taken together, the indicated poles fall into groups according to time intervals. Within each of these groups there is little difference among the poles, and what differences there are do not fall into chronological order. The "mean poles" of each group, however, do lie in chronological order, and the transitions between each group seem to have come about quickly. Briden concludes that in Gondwanaland, at least, there was no drift at all during long "quasistatic intervals," and that drifting occurred during short "drift periods." There is some evidence of a correlation among the drift periods, important mountain-building episodes and times when there were sharp breaks in the history of animal species. These breaks, in turn, have been correlated with reversals in the magnetic field of the earth (see "Reversals of the Earth's Magnetic Field," by Allan Cox, G. Brent Dalrymple and Richard R. Doell; SCIENTIFIC AMERICAN, February).

Tools of Conjugation

A class of bacterial appendages that has been under study for some 15 years is turning out to play a number of important roles in the transfer of molecules into and out of bacterial cells. The appendages are pili, hairlike tubules that are sometimes present on the surface of most gram-negative bacteria. More than a dozen different kinds of pili have been distinguished since they were identified by Charles C. Brinton, Jr., and his colleagues at the University of Pittsburgh in 1954. Two kinds, the *F* and the *I* pili, are apparently conductors of nucleic acid across the cell membrane, and as such are both the sites of infection of these cells by certain phages, or bacterial viruses, and the means by which one cell passes genetic material to another in the process known as conjugation.

Brinton's group has purified and crystallized pili and found them to be composed of protein subunits. Analysis of one kind of pili, the Type 1, by X-ray diffraction has revealed a regular helical configuration of the subunits. The function of the Type 1 pili is not known, but several interesting functions have been discovered for what are called "sex pili." E. M. Crawford and R. F. Gesteland, then at Harvard University, noted in 1964 that certain phages that infect only male bacteria are adsorbed by pili. Brinton and his co-workers identified these as *F* pili, which are generally under the genetic control of the fertility factor (*F*), present only in male bacteria. Electron micrographs suggest that male-specific phages with ribonucleic acid (RNA) as their genetic material inject the RNA into the side of the *F* pili, whence it travels through the axial hole in the pili to penetrate the bacterium. Phages with deoxyribonucleic acid seem to inject the DNA through the end of the pili.

In 1964 the Pittsburgh group was able to demonstrate that the *F* pili are the route through which male cells transfer to female cells genetic information—including the *F* factor itself, *F*-mediated pieces of male chromosome and other chromosomal and cytoplasmic elements. In London, Elinor Meynell of Hammersmith Hospital, Naomi Datta of the Royal Postgraduate Medical School and A. M. Lawn and G. G. Meynell of the Lister Institute of Preventive Medicine subsequently found that the *F* pili and the related *I* pili were also responsible for infectious drug resistance. This is the process in which a resistance factor, *R*, imparts, to a previously drug-sensitive strain of bacteria, resistance to a number of antibacterial drugs (see "Infectious Drug Resistance," by Tsutomu Watanabe, page 19). The four English workers recently reported in *Nature* that the *F* and *I* pili seem to account for all known forms of bacterial conjugation.

Old Seeds

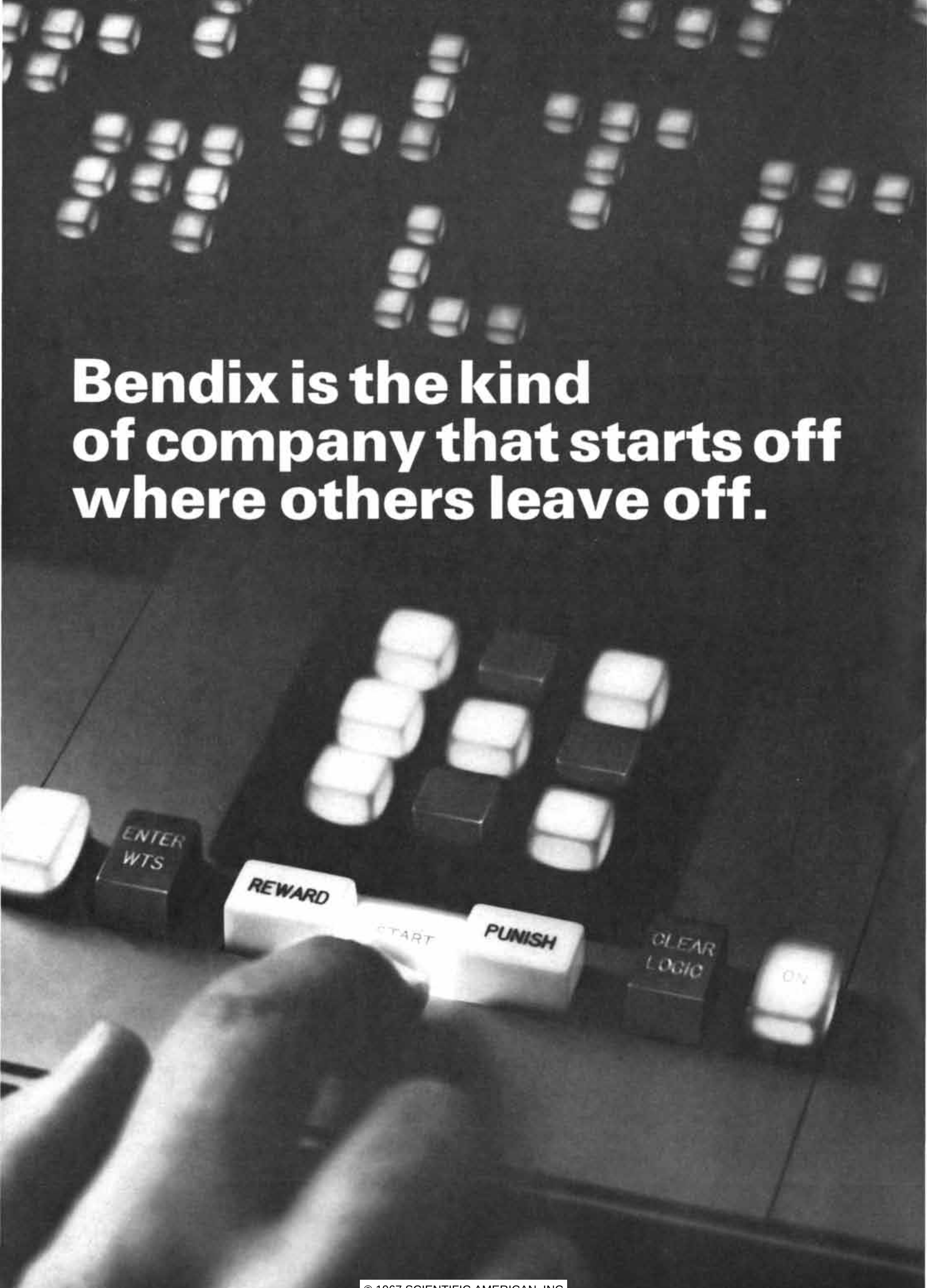
Tales of crops raised from seed found in some forgotten Pharaoh's tomb make botanists' eyebrows rise: a seed's ability to germinate is usually lost in a few years or a few decades at most. Until recently the longevity record was held by some lotus seeds that were successfully germinated after 2,000 years of burial in a Japanese bog. The record has now been surpassed by some seeds of arctic lupine, found in 1954 in the midst of a 36-foot deposit of permanently frozen muck cut through by placer miners near Miller Creek in Canada's Yukon Territory. Muck deposits in the area, formed late in Pleistocene times, contain the bones of extinct mammals and are believed to be at least 10,000 years old.

Ancient lemming burrows were exposed by the miners' cut, whereupon Harold Schmidt, a Yukon mining engineer, removed a lemming skull and several seeds from the burrows. Twelve years passed before a staff member of the National Museum of Canada, traveling in the Yukon, heard of Schmidt's find. Fortunately the seeds had been kept dry in the interim and a number of the best-preserved ones were taken to Ottawa. When placed on wet filter paper, six of them germinated within 48 hours. According to a report in *Science*, the six have now grown into healthy plants indistinguishable from today's arctic lupine.

Fast Type

The world's fastest typesetting machine, the Linotron, has been placed in operation at the U.S. Government Printing Office in Washington. It is an electronic system that sets type of letterpress quality, an entire page at a time, at rates up to 1,000 characters a second, using a programmed computer tape as input. The system was developed by the CBS Laboratories and the Mergenthaler Linotype Company. Its primary function will be to set the vast quantities of Government publications, such as stock lists, that are generated by data-processing systems. The standard way to print such material is to copy the computer printout photographically to make plates for photo-offset reproduction. The printout is fast but is considered hard to read and wasteful of space, and the resulting volumes are bulky. An alternative would be to set the type by conventional high-quality methods, but these methods are too slow to keep up with digital computers.

The heart of the new system is the character generator, an electronic tube. From a 4½-inch-square glass grid, an array of 256 letters, numerals and symbols in several styles is projected onto the face of a tube much like that of a television camera. Each character is controlled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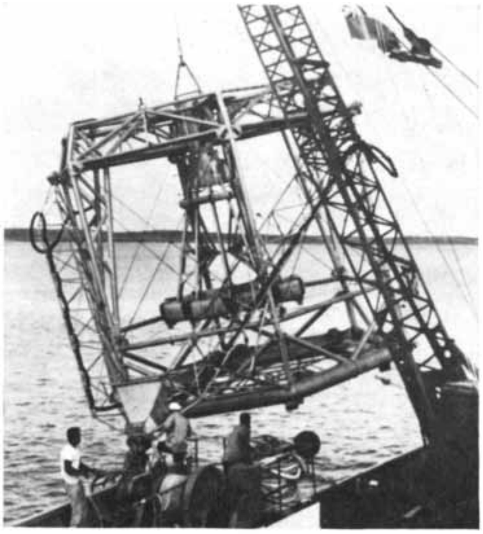
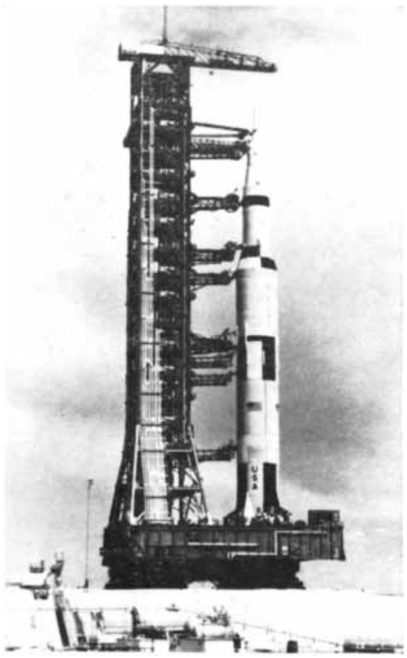


Take a dip into navigation. This giant Bendix transducer is being lowered into 2,000 feet of water for an experiment in underwater sound research. Acoustic transducer systems have a bright future in both defense and commercial applications.



Take a giant step. As NASA's new space workhorse—mighty Saturn V—moves to the launch pad, Bendix is there. The 2,300 Bendix people at Kennedy Space Center operate and maintain key systems in everything from the vertical assembly building to the huge transporter that carries the 30-story Saturn V and its even larger mobile launcher to the pad.

Take this surprising Bendix machine, for example: It has the ability to learn. Much as you might train a human, a Bendix technician is actually training this device to recognize visual patterns. When the Adaptive Pattern Recognizer gives a wrong answer, the technician pushes the "punish" button—and for a correct response, a "reward" signal. Someday, machines with trainable logic circuits may forecast weather, control spacecraft, sort luggage and read mail. It's an interesting example of how Bendix takes the current state-of-the-art in a particular technology and builds on it. In automation—as well as in aerospace, electronics, automotive and oceanics—the heart of our business is creating new ideas and developing them to maximum usefulness. The Bendix Corporation / Fisher Building / Detroit, Michigan 48202.

Bendix

Where ideas unlock the future

by an electronic "gate." The input to the Linotron, a magnetic tape on which the data to be published have been combined with a program governing the format of the pages, controls the opening of these gates. As each character is called for, it is converted from a visual image into a video signal and projected in the proper position on the screen of a cathode-ray tube. The tube's resolution is 180 times finer than that of a commercial television tube, and the tube is corrected for distortion. As the characters appear on the screen (too fast for the eye to detect) they are recorded on film, which provides the plates for offset reproduction.

There are three additional glass grids, which can be positioned in half a second, to provide more typefaces. The size of the letters, from 6 point to 18 point, is varied electronically. The speed of typesetting varies with the size—1,000 characters per second for 6-point type, 800 for 8-point (the size of the illustration captions in this magazine) and 620 for 10-point. A 4,000-character page set in 8-point type can be produced at about 600 pages an hour, including the half-second required to advance the film between pages. A second version of the Linotron, being designed for the Air Force, will reproduce artwork as well as type by means of videotape spliced into the computer tape.

Franklin Revisited

A group of investigators has borrowed and refined the technique of Benjamin Franklin's most familiar experiment in order to achieve what the 18th-century pioneer in studies of electricity fortunately avoided: the triggering of a lightning stroke. Using rockets rather than a kite, M. M. Newman of the Lightning and Transients Research Institute and co-workers from the institute, from the Federal Aviation Agency and from the Air Force have fired strands of fine stainless-steel wire aloft in the vicinity of storm clouds from the deck of a research ship. They have thereby successfully triggered lightning strokes that first leap from the cloud to the wire—which is instantly vaporized—and then travel to the ship's deck. In a single day's work off St. Petersburg, Fla., in August, 1966, 17 out of 23 rocket firings, each carrying an average of 300 feet of wire skyward, were answered by lightning strokes from a cloud 3,000 feet overhead to the instrumented impact point on shipboard.

As a result Newman and his associates are beginning to collect useful quantitative data. In a recent letter to the *Journal of Geophysical Research* they list some preliminary findings. Item: As many as nine strokes of diminishing force follow within half a millisecond of the first stroke. Item: The maximum current comprising the first stroke averages some 40,000 amperes. Item: The total negative charge lowered from cloud to ground by the first stroke is approximately one coulomb.

Low-Friction Rollers

A new concept that promises to yield an almost frictionless device with revolutionary implications for mechanical engineering has passed beyond the design stage to the point of laboratory testing. Developed by Donald F. Wilkes, a mechanical engineer on the staff of the Sandia Corporation, the nuclear-weapons laboratory operated by the Western Electric Company in Albuquerque, N.M., for the Atomic Energy Commission, the device in its simplest form consists of a boxlike rectangular cage within which two cylinders are held by the opposing curves of an S-shaped strip of springy material. The cylinders roll back and forth freely, rotating in opposite directions, but their motion is almost without friction because the area of contact between strip and rollers remains the same at all times. When the device is lightly loaded (pressures from 500 to 3,000 pounds per square inch), coefficients of friction as low as .0005 can be attained without the use of lubricants. This is a tenth of the friction encountered in conventional bearings.

The device, christened "Rolamite," is a product of the search for suspension systems to be used in subminiature components of nuclear weapons. Because the roller-and-spring assembly does not require precision finishing, it can be produced in miniature sizes at relatively low cost. It is estimated that, in various configurations, the Rolamite principle has at least 50 major applications, including bearing assemblies, shock absorbers, dampers, pistons, firing pins, pumps, relays, speed-changers, sensing devices, thermostats, hinges, locks and switches. The AEC has filed a patent application in Wilkes' name that covers a large family of Rolamite devices; such patents permit licensed manufacture without royalty payments. Sandia Corporation officials think it possible that the low-friction configurations will affect mechanical and electromechanical design as radically as the transistor affected electronic design.

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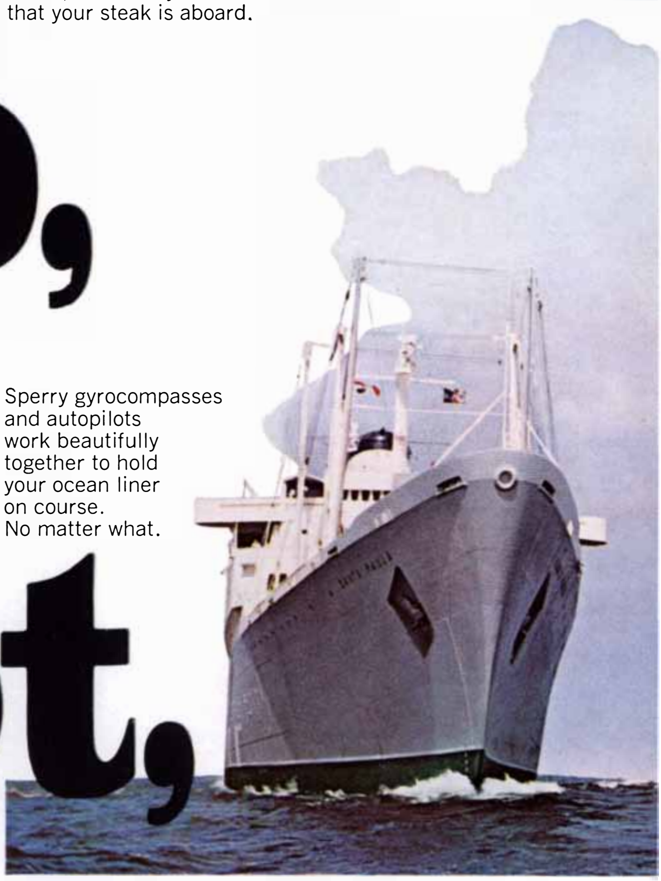

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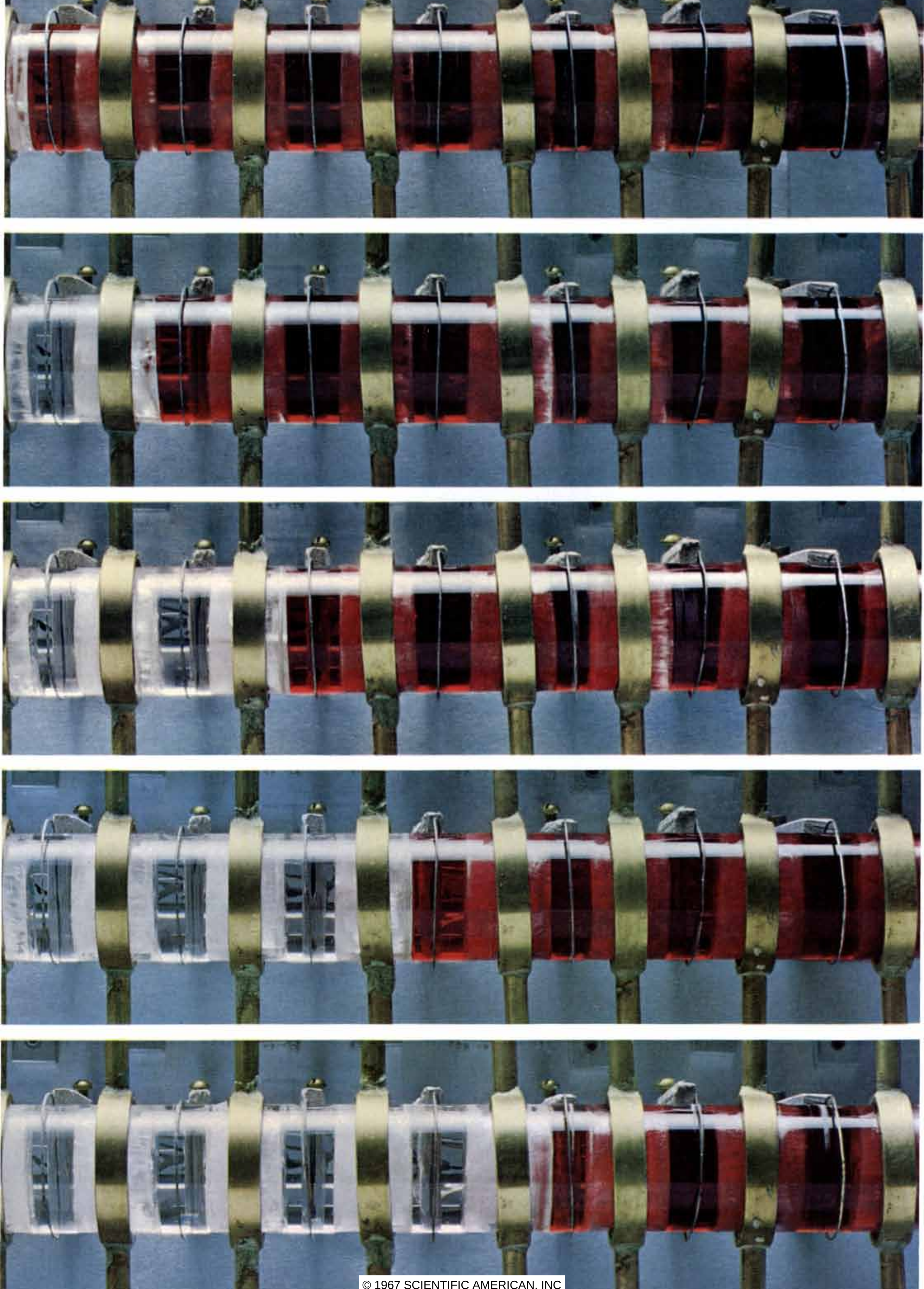


ZONE REFINING

This simple technique, in which a solid is refined by passing a liquid zone through it, has been of profound value in those technologies that call for materials of extremely high purity

by William G. Pfann

About a third of the elements and hundreds of organic and inorganic compounds have been produced in their purest form by a simple technique called zone refining. If two of these elements, germanium and silicon, had not been available in the desired purity, the whole development of solid-state electronics would have been crippled. Other elements, when highly purified, have revealed their true properties for the first time, leading to new fields of research. All of this has happened since the basic paper on zone refining was published in 1952.

What is zone refining? It is one of a general family of techniques known as zone melting, by which materials can be purified or given desired compositions or variations of composition. In zone melting a short liquid (or molten) zone travels through a relatively long charge (or ingot) of solid, carrying with it a portion of the soluble impurities in the charge. The final distribution of impurities, or components, depends on the size, number and direction of travel of the zones, on the distribution of impurity in the original charge and on an intrinsic property of the impurity known as the distribution coefficient.

In zone refining, which is probably the most important zone melting technique, a number of molten zones are passed through the charge in one direction. Each moving zone carries a fraction of the impurities to the end or, in some cases, to the beginning of the charge, thereby purifying the remainder and concentrating impurities at one or both ends. In the 15 years since my original paper on the subject I have been asked over and over: "How could such a simple idea have been missed all these decades? How did you think of it?"

I really cannot answer either question. Several years after my paper had appeared I learned that Peter Kapitza, the Russian physicist, had actually performed a one-pass zone melting operation and had described it in a paper published in 1928. He was concerned with crystal growth, however, and apparently did not recognize the potential of a molten zone as a distributor of solutes, and it would seem that neither did any of the hundreds of physicists who must have read his paper.

My own conception of the process dates back to 1939, when the late Earle E. Schumacher, head of the metallurgy laboratory of the Bell Telephone Laboratories, told me I could spend half my time on fundamental research of my own choosing. I chose to study "slip bands" produced by deforming single crystals of lead containing a fraction of a percent of antimony. I recognized that if I used a standard freezing technique to grow the crystals, the antimony would tend to segregate, thus producing a crystal with a nonuniform distribution of the solute. To remedy this I thought to grow the crystal by passing a short melted zone along the ingot in the hope of leveling out the distribution of antimony. This procedure, now called zone leveling, did not strike me as particularly remarkable and nothing came of it at the time. I assumed that such a simple idea must be common knowledge. Also, about that time Bell Laboratories became heavily engaged in technical problems of World War II. It was not until years later, when the need arose for germanium of uniform purity for transistors, that I again thought of zone leveling. Suddenly the lightning of zone refining struck: a molten zone moving through an ingot could do more than level out impurities—it could remove them.

With the help of colleagues at Bell Laboratories zone refining was quickly developed into a successful manufacturing procedure. The purity achieved was spectacular. The harmful impurities—those affecting transistor properties—were reduced to less than one atom of impurity in 10 billion atoms of germanium. This ratio is equivalent to a grain of salt in a freight-car load of sugar. Since then zone refining has been applied successfully to many other semiconductors and metals, as well as to organic and inorganic compounds.

In order to understand zone refining, and zone melting in general, one must understand what is meant by the distri-

ROTATION-CONVECTION ZONE REFINER, shown in operation on the opposite page, illustrates how a traveling molten zone can remove impurities from a material. The material in this case is naphthalene, to which a red dye has been added. The first step of the sequence (*top*) shows the dye uniformly distributed among molten zones and crystallized zones that alternate inside a one-inch glass cylinder, which rotates a few times a minute. The molten zones are created by single-turn Nichrome heaters. The adjacent zones are solidified by a flow of cooling water between loose-fitting brass rings and the surface of the glass cylinder. The rotation of the cylinder produces liquid-solid interfaces that are practically flat and promotes diffusion in the liquid region. The cylinder travels to the left at the rate of about two centimeters an hour, thus sweeping the molten zones to the right. In addition the cylinder has a ratchet motion resembling that of a typewriter carriage: after traveling slowly to the left one heater spacing it jumps quickly to the right the same distance. Thus the purified zones are carried to the right in the manner illustrated. The rotation-convection zone refiner was built by the author and his colleagues at Bell Telephone Laboratories.

bution coefficient. A solution of salt in water provides a familiar example. When the temperature of such a solution is lowered to the freezing point, the first ice crystals to form do not contain the same concentration of salt as the original solution does. In fact, the ice crystals contain a significantly lower concentration because the salt redistributes itself between the solid phase and the liquid phase while the crystal is being formed. The distribution coefficient is defined as the concentration of the solute in the solid divided by its concentration in the liquid; thus the coefficient is less than one. Indeed, for ordinary table salt in freezing water, the distribution coefficient is close to zero, meaning that salt is almost totally excluded from ice crystals as they form. As a consequence the concentration of solute in the remaining solution tends to rise steadily until all the liquid is frozen. When the solute is not table salt but a more typical substance, the crystals become progressively richer in the solute as they freeze from a more and more concentrated solution. Concomitantly the freezing point of the solution drops steadily as the solute concentration of the remaining solution rises.

All of this can be summed up in a phase diagram that shows how the composition of the liquid phase (bounded by the "liquidus" curve) is related under equilibrium conditions to the composition of the solid (bounded by the "solidus" curve) for all concentrations of the solute in the solvent, together with the freezing point for each concentration [*see illustration below*].

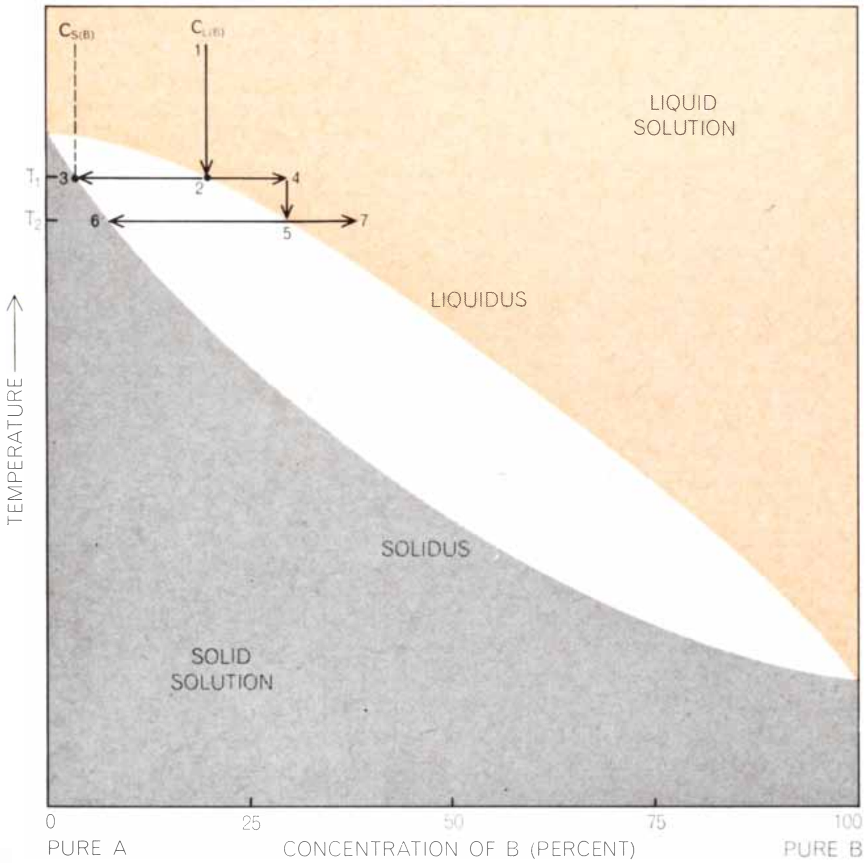
There is an equilibrium, or ideal, distribution coefficient, designated k_0, and an effective value, designated k. The whole success of zone refining depends on the fact that under ordinary freezing conditions equilibrium is far from being achieved. If freezing of, say, a solution or an alloy took place so slowly that the *entire* solid at all times had the composition of the solidus curve in the phase diagram, the last crystals to form would have the same composition as the entire solid. This implies, in turn, that the final frozen solid would have precisely the same solute concentration as the original solution. Paradoxically equilibrium freezing consists in two simultaneous and opposed processes: the rejection of the solute by the advancing solid-liquid interface and the diffusion of the solute back into the solid that has frozen.

In practice equilibrium freezing is almost impossible to achieve if one is dealing with substantial volumes of material. Diffusion rates in solids are almost always too low to permit back diffusion of the solute. For practical purposes, therefore, the solute-rejection process is the only one that counts. In consequence a severe segregation of the solute is achieved; the last solid to freeze will normally contain a much higher concentration of the solute than existed in the original solution.

In normal freezing, back diffusion is effectively prevented if the solid-liquid interface advances at a rate of from one to 20 centimeters per hour. This speed is also usually slow enough so that the concentration of solute in the liquid is equalized by diffusion or convection. Under these conditions the solute distribution along an ingot will follow that predicted by a normal freezing curve for some constant value of k, say .5 [*see illustrations on opposite page*]. At low solute concentrations the assumption of constant k is reasonable.

Mixing processes in the liquid can include forced convection in addition to natural convection and diffusion. If the mixing is rapid enough, the effective distribution coefficient, k, will approach the equilibrium, or ideal, value, k_0. But if the mixing is sluggish, solute will accumulate in the liquid at the advancing solid-liquid interface, with the result that k will be larger than k_0 and will lie between k_0 and unity. An effective distribution of unity implies, of course, no segregation, because the concentration of solute in the newly formed solid will exactly equal that in the bulk of the liquid.

Let us now consider what happens if a single molten zone is passed through a solid cylinder, or ingot, that has a uni-



PHASE DIAGRAM for a binary system of two components, *A* and *B*, clarifies the relations on which zone refining is based. The diagram shows that adding solute *B* to solvent *A* lowers the freezing point of an *A*-rich solution. Conversely, adding *A* to *B* raises the freezing point of a *B*-rich solution. Zone refining works because the composition of the solid that freezes out at any given temperature differs from the composition of the solution. Thus if a solution of composition *1* is lowered to its freezing point, *2*, the solid that forms, *3*, contains much less *B* than the original liquid. The exclusion of some *B* from the solid raises the concentration of *B* in the remaining liquid, *4*, which now has a lower freezing point, *5*. Again the solid that forms, *6*, excludes *B* and raises the concentration of *B* in the liquid, *7*, and so on. The critical relation is the equilibrium distribution coefficient, k_0, defined as the ratio of "solidus" concentration to "liquidus" concentration at a given temperature. Here that ratio is $C_{S(B)}/C_{L(B)}$. The effective distribution coefficient, k, is usually higher than k_0.

form concentration of solute B in solvent A [*see illustrations at right*]. Let the initial concentration of B in A be represented by C_0. It is not necessary that the ingot be an ordinary rapidly frozen casting; it can be a mixture of sintered powders or even two long rods side by side whose cross section at any point corresponds to concentration C_0.

A molten zone, say a tenth of the length of the ingot, is formed by a heating coil placed at one end of the charge. The heating coil is then moved slowly along the charge. As it advances, the first solid to freeze behind it has a concentration of solute B equal to C_0 times the distribution coefficient k, or kC_0. Since k is less than one, the newly formed solid contains less of solute B than the original charge does. This means that some of B must be rejected into the molten zone, raising its concentration of B. Simultaneously solid of concentration C_0 is being melted into the zone at its leading interface. These concurrent processes increase the solute concentration in the molten zone and also in the solid that is freezing at the trailing interface.

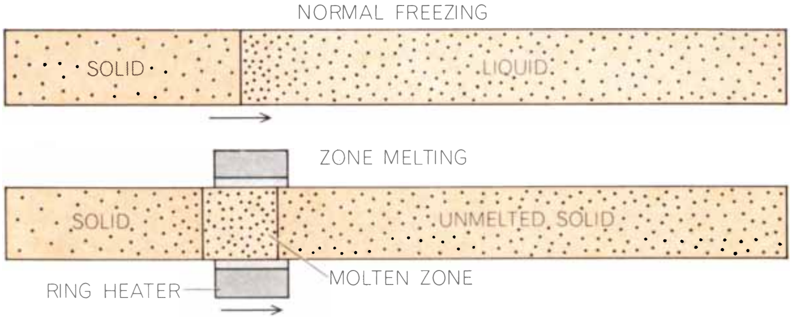
This rise continues until the solute concentration in the molten zone reaches the value C_0/k. At that point the concentrations of solid entering and leaving the zone are equal. The concentrations in the liquid and in the freezing-out solid now remain constant for several zone lengths, producing a region of zone leveling—the phenomenon that I erroneously thought was common knowledge in 1939. Zone leveling continues until the front of the molten zone reaches the end of the ingot. From there on the volume of liquid decreases as in normal freezing and the solute concentration follows a normal freezing curve in the last zone length of the ingot.

Thus the net effect of passing a molten zone through an ingot just once is to produce an ingot with three regions: a region of purification in which the solute concentration rises rather steeply from kC_0 to C_0, a "zone-leveled" region of concentration C_0 and a short terminal region in which the concentration greatly exceeds C_0. Single-pass zone melting, therefore, is neither fish nor fowl. As a purification step it is actually less effective than one normal freezing step and as a leveling step it leaves much to be desired.

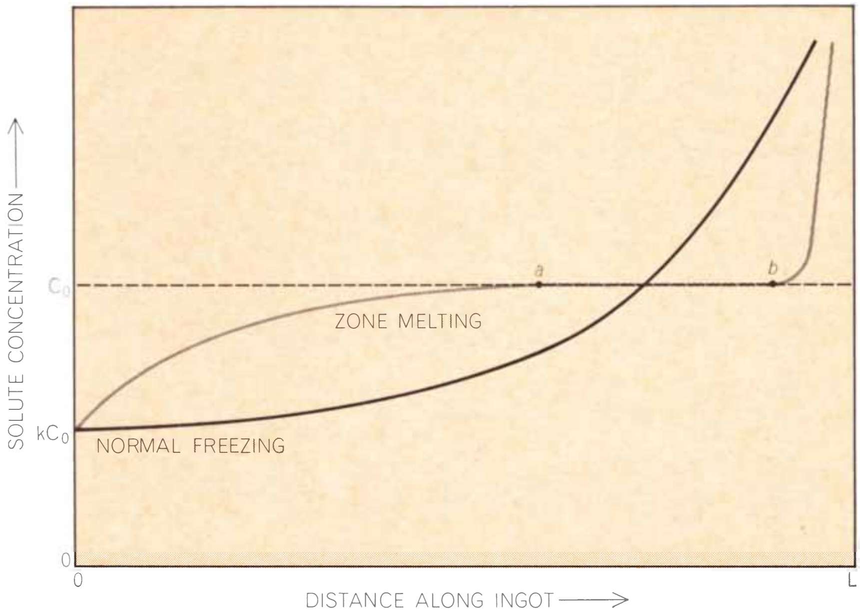
The "secret" of zone refining, which now seems altogether obvious, is to pass a molten zone through an ingot *repeatedly*. The idea of using repeated crystallizations to purify substances is actually very old. The impure substance was dissolved in a solvent (itself a source of contamination); the solution was cooled to freeze out a fraction of crystals (by normal freezing), then the partly purified crystal fraction was separated from the "mother liquor" and redissolved. The operation was repeated many times on both the crystals and the liquors, with recombination of various fractions in accord with a complicated procedure. Because it was tedious and time-consuming, repeated fractional crystallization was never widely adopted as a purification procedure.

By means of zone refining, the old idea of repeated fractional crystallization is converted from a cumbersome process into an extremely simple one. With little difficulty several molten zones can be passed through an ingot, one behind the other, with each zone-pass comprising a step of crystallization. Moreover, the ingot can be subjected to as many zone-passes as desired, increasing its purity each time, without the troublesome handling of fractions. This is the main advantage of zone refining. The charge does not have to be touched, or even moved, until the process is finished.

The effect of multizone passes can readily be appreciated. Suppose the original ingot contains 1 percent of some

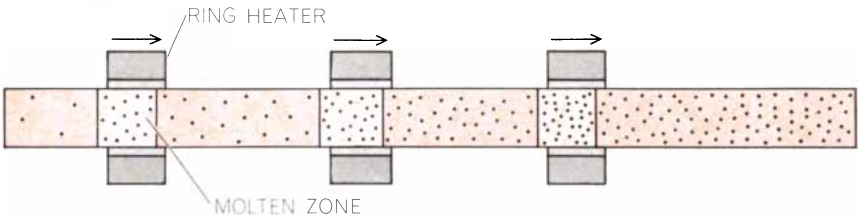


ORDINARY FREEZING AND ZONE MELTING both alter the distribution of a solute in a solvent. Oddly enough, one-pass zone melting (*bottom*) is actually less effective as a refining method than normal freezing (*top*). This can be inferred from the illustration below.

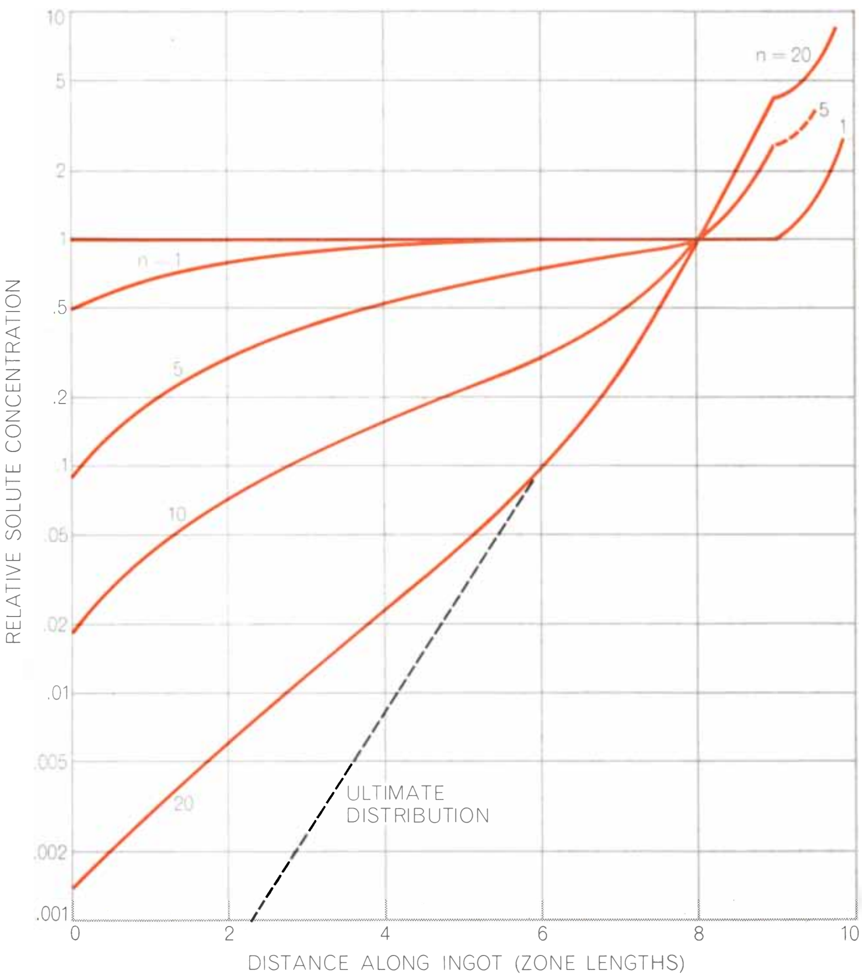


IMPURITY DISTRIBUTION produced by normal freezing and that produced by one-pass zone melting are quite different. The curves are plotted for sample charges of the same initial concentration of solute (C_0) and the same distribution coefficient (.5). The amount of solute, or impurity, in the newly formed solid rises much more steeply in zone melting than in normal freezing. The virtues of zone melting emerge, however, when a molten zone is passed through an ingot many times (*see illustrations on next page*). Moreover, the flat region between *a* and *b* in the zone melting curve can be exploited to produce an ingot whose content of a desired impurity is extremely uniform. This process is termed zone leveling.

impurity and that the distribution coefficient k is .5. The first solid to freeze behind the first pass of a molten zone will contain .5 percent of impurity. If k remains .5, the first solid to freeze behind the second pass will contain .5 times the average concentration of impurity in the first zone length. It is easy to compute that 10 passes through a charge 10 zone lengths long will reduce the initial concentration of a given impurity by 98 percent and that 20 passes will reduce the concentration by about 99.85 percent [*see lower illustration below*]. The ultimate distribution varies exponentially with the distance from the beginning of the charge and thus appears as a straight line when plotted on semilog paper. Such calculations have been verified experimentally.



MULTIPASS ZONE MELTING, more commonly called zone refining, was first described by the author in 1952. For speed and convenience several molten zones are passed through an ingot simultaneously. Each is as effective as a single molten zone traveling alone.



PURIFICATION ATTAINABLE BY ZONE REFINING is shown in this family of curves for one, five, 10 and 20 passes of a molten zone through an ingot 10 zone lengths long. The purification is for a distribution coefficient of .5. The ultimate distribution is the one theoretically attainable after many zone passes. Although the curves were generated by a computer, they have been confirmed in actual practice. In germanium and silicon ingots used for making transistors, harmful impurities are routinely reduced to less than one part in 10 billion.

The ultimate distribution represents the maximum purification attainable. It is something like piling sand against a wall. There is a maximum height for a given amount of sand. In zone refining the ultimate distribution is the steady state reached by two opposing fluxes. The first is the ability of the freezing interface to reject solute, roughly proportional to the absolute value of $1 - k$. The second is the rapid mixing effect, proportional to the square of the length of the zone, which causes freshly dissolved solute to migrate backward from the melting interface to the freezing interface of the zone. The purification represented by the ultimate distribution is roughly proportional to (and very sensitive to) the number of zone lengths in the charge and to the value of k [*see illustration on opposite page*].

I mentioned earlier that impurities sometimes travel opposite to the direction of zone travel and accumulate at the *front* of the charge. How is that possible? This happens when k for a particular solute is *greater* than unity. In the case of an ordinary solute, which lowers the melting point of the solvent, k is less than unity. But in the typical phase diagram showing liquidus and solidus curves it is also possible to select a composition at the far right where the major component (B) is regarded as the solvent and the minor component (A) as the solute (whereas at the left of the diagram the roles are reversed). In this region of the diagram the concentration of the solute (A) in the freezing-out solid is *greater* than in the liquid; hence k is greater than unity. Such a solute also raises the freezing point of the solvent. In both normal freezing and in zone refining such solutes travel backward and become concentrated at the front of the ingot.

To achieve zone leveling, so important in producing single crystals of germanium and silicon with a uniform concentration of desired impurities, one exploits the characteristics of a solute with a very low distribution coefficient (a k of about .005). The simplest procedure is to use a seed crystal of desired orientation and to place a pellet of low-k solute at the beginning of a charge of pure germanium or silicon. This may seem paradoxical because in normal freezing low-k solutes produce the greatest segregation. When used in zone leveling, however, a low-k solute stays predominantly in the molten zone, so that the concentration in the melt is typically some 200 times higher than it is in the solid freezing out at the trailing interface. The net effect is that a slight and virtually uniform amount of solute is left behind in the solid as the zone travels through the ingot.

Germanium was the first element to be ultrapurified by zone refining. Except for the addition of automatic controls, the present-day commercial process [*see top illustration on next page*] hardly differs from the original laboratory one. An ingot of germanium is placed in a "boat" of high-purity graphite and subjected to repeated zone meltings in an inert atmosphere of nitrogen.

A Zone That Floats

When the same technique was tried with silicon, however, problems developed. The silicon became contaminated because no boat could be found that was not wetted by the molten silicon. The problem was solved, and a wide area of investigation was opened, when my colleague Henry C. Theuerer invented the floating-zone technique. The technique was subsequently discovered by others: by the late Paul H. Keck and Marcel J. E. Golay of the U.S. Army Signal Corps Laboratories in Fort Monmouth, N.J. (who published first and gave the technique its name), and by R. Emeis of Siemens and Halske.

In this refining method a rod of silicon is clamped in a vertical position, held only at the ends. An unsupported, or floating, molten zone extending through the cross section is produced by a water-cooled induction heating coil. Refining is accomplished by moving the floating zone repeatedly from one end of the rod to the other. Today industry routinely turns out float-zoned single crystals of silicon about four centimeters in diameter and about 30 centimeters long [*see bottom illustration on next page*]. Since a transistor today uses less than a milligram of silicon, such a crystal represents many tens of thousands of devices.

It is perhaps obvious that only one molten zone can be passed through an ingot at a time in the float-zone technique. If two zones were introduced, the solid region between the two—being unsupported—would simply collapse the lower zone. It may be surprising, nevertheless, that surface tension is quite adequate to support a single molten zone, provided that a certain height is not exceeded. In this regard nature has been kind. The highest-melting metals, being extremely reactive when molten, are most in need of the float-zone technique for refining. Fortunately surface tension increases with melting temperature and thus allows a large molten zone. Certain

ULTIMATE DISTRIBUTION CURVES are critically dependent on the effective distribution coefficient, *k*, and on the length of the ingot, measured in zone lengths. Here for an ingot of 10 zone lengths are the ultimate distribution curves when *k* is .1 and when *k* is .5.

very stable inorganic compounds also lend themselves to float-zone treatment. Water, because of its anomalously high surface tension and its low density, could also be purified by the float-zone method if one wished.

At very high temperatures, say above 1,500 degrees centigrade, float-zone purification occurs partly by volatilization of impurities and partly by zone refining. An effective way to create a floating molten zone in a high-melting metal is to place a ring-shaped cathode around the rod to be refined, which serves as the anode. Electrons from the cathode bombard the rod and melt it. An electron-beam refiner of this kind, built by the Materials Research Corporation, appears on the cover of this issue of *Scientific American*. The ingot in the photograph is titanium.

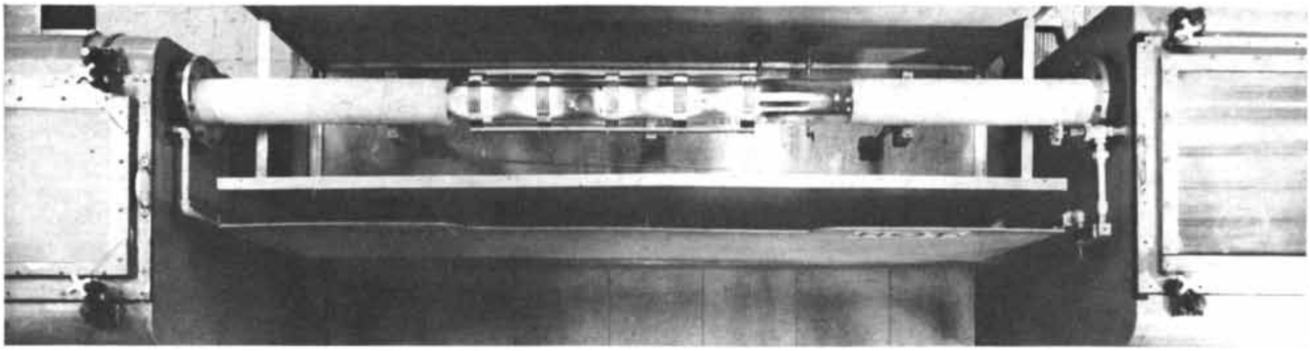
Mechanical, chemical, electrical and magnetic properties of a metal often change strikingly when it is made really pure. For example, Raymond L. Smith and John L. Rutherford, then at the Franklin Institute, showed that float-zone-refined iron remained ductile even when cooled to the temperature of liquid helium (4.2 degrees C. above absolute zero). In the laboratory of Georges Chaudron at Vitry-sur-Seine in France it has been found that in zone-refined iron the solubility of oxygen and hydrogen falls below the limits of detection and that resistance to oxidation increases.

Ductility in general increases remarkably when metals are made very pure. Beryllium is ordinarily an extremely hard and brittle metal at room temperature. Yet a crystal rod of beryllium 1.5 centimeters in diameter, purified by float-zoning in a high vacuum, turned out to be so ductile that it could be bent by hand into a complete circle. The purification was done at the Nuclear Energy Research Institute at Grenoble by B. Schaub.

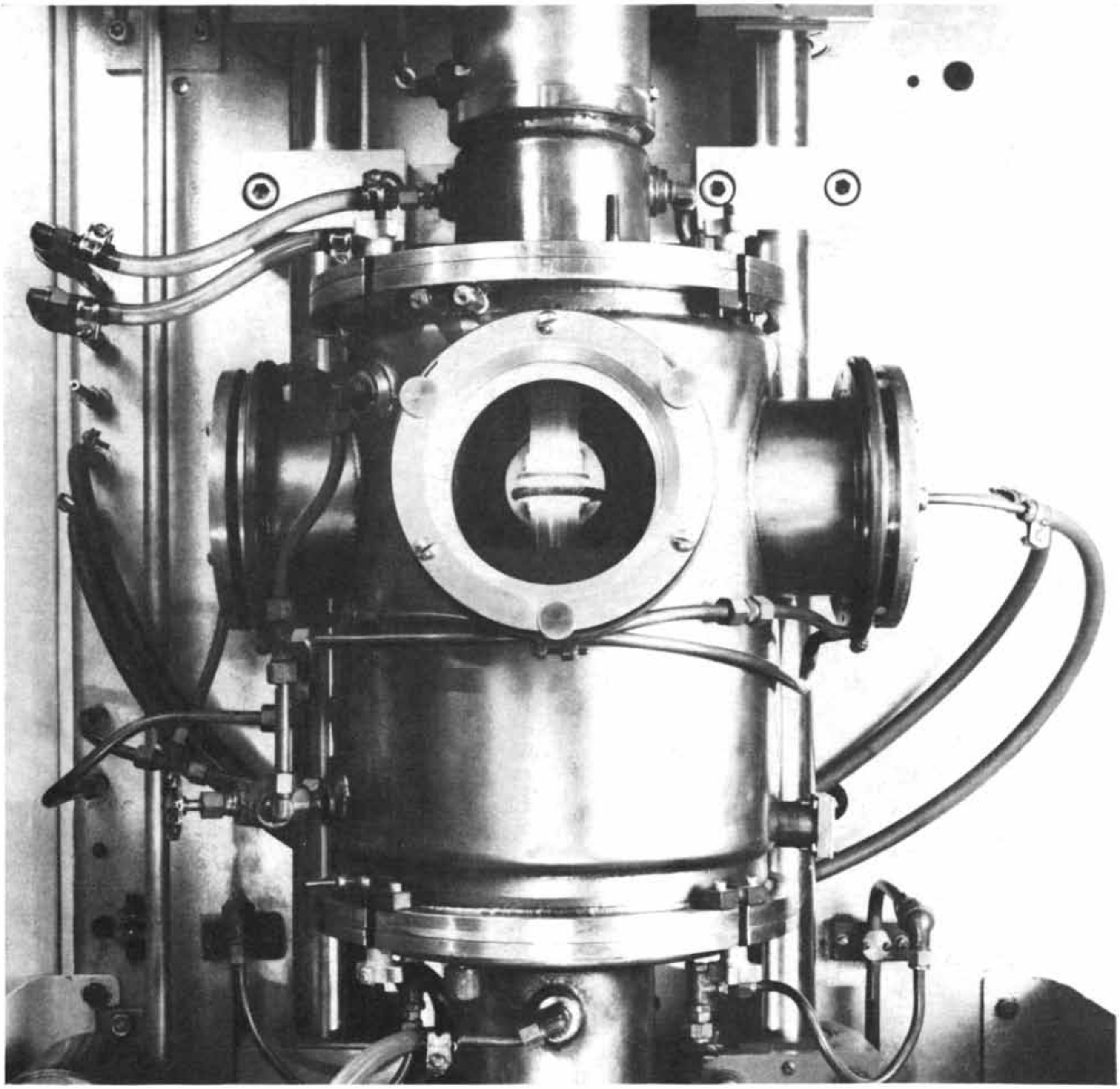
Not many years ago the phenomenon of superconductivity—the ability of a metal to carry an electric current without resistance at very low temperatures—was thought to be restricted to a modest group of metals and not particularly sensitive to the metal's purity. But recently molybdenum and tungsten were shown to be superconductors when the magnetic impurity iron was reduced to a very low level. Highly purified beryllium has similarly proved to be a superconductor; the critical impurity remains to be established.

The actual velocity of grain-boundary migration in zone-refined lead of extreme purity was measured by J. W. Rutter and K. T. Aust of the General Electric Research Laboratory. They found that as little as three parts per million of silver reduced the velocity of migration by a factor of a thousand.

The General Electric Company has recently described how it employs zone refining to produce copper of exceptional purity for use in vacuum circuit breakers. For heavy-duty service these devices require electrode faces that are extremely free of gas, otherwise undesirable arcing occurs when the circuit is broken. Zone refining enables General Electric to produce copper with the necessary low gas content: less than one atom of gas per 10 million atoms of copper. Too low



PRODUCTION ZONE REFINER at the plant of the Western Electric Company in Allentown, Pa., is shown from above. Ingots of germanium feed in automatically from the right, are refined by passing through five induction heating coils and emerge at the left.



FLOAT-ZONE REFINER, also at Western Electric, converts ingots of silicon into single crystals of controlled purity by passing them vertically through an induction heating coil. The molten zone is held in place by surface tension. By adding trace amounts of desirable impurities to the controlled atmosphere surrounding the ingots, the properties of the finished silicon can be varied.

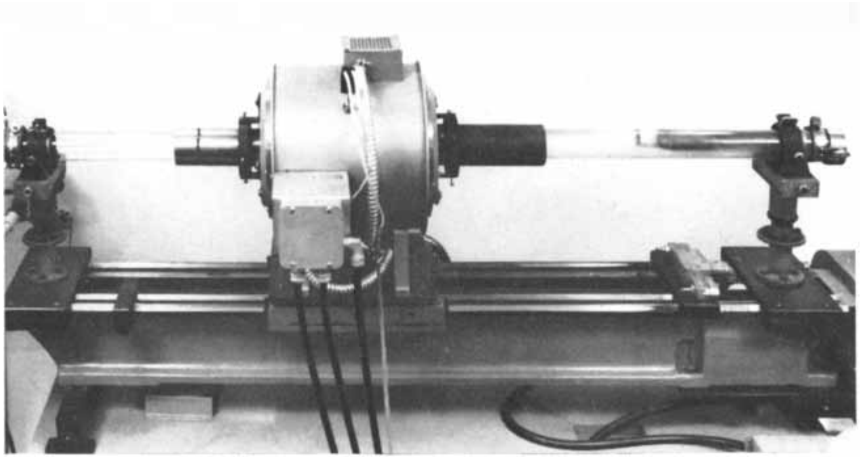
to measure analytically, the gas content can be inferred by building a circuit breaker and testing it under operating conditions.

Some Special Zone Refiners

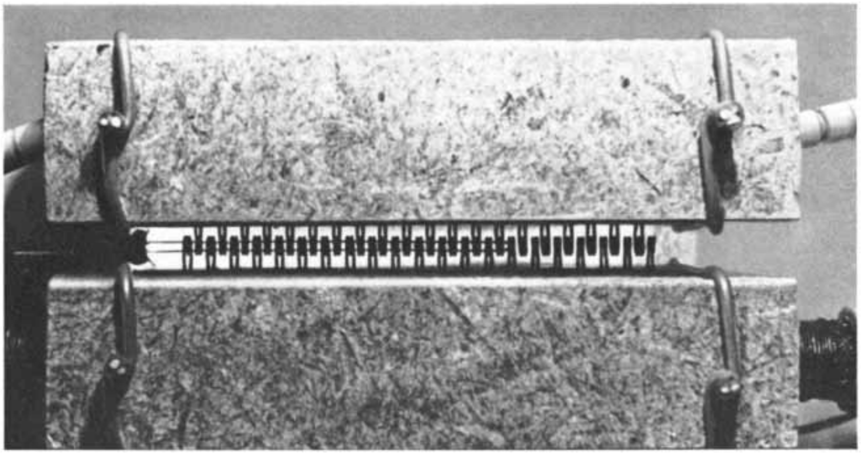
In any zone refining operation, time is saved if the zones are short and close together. Shortening the zone length, moreover, results in greater purity in a given length of ingot. The problem of achieving short zone length and short interzone spacing is particularly difficult for organic compounds. On the whole their thermal conductivity is very low, about a thousandth that of metals, so that it is difficult to remove the heat of fusion liberated at the rear, or freezing, interface of the zone. If the heat of fusion is not removed efficiently, the zone gets longer.

Ideally the zone refiner should have closely spaced, alternate arrays of heat sources and heat sinks. A beautiful example of such apparatus is a microscale zone refiner developed by Hermann Schildknecht and H. Vetter at Erlangen University. The refiner, which handles ingots weighing only a few milligrams, compresses 20 hot zones and 20 cold ones in a distance of six centimeters [*see lower illustration at right*]. Schildknecht and Klaus Maas have since built an even smaller zone refiner that can treat less than 100 micrograms of material. His group, now at the University of Heidelberg, has become the leader in the zone refining of organic compounds. For example, Schildknecht's group determined for the first time the true melting points of the homologous series of fatty alcohols ($C_nH_{2n+1}OH$) from C_{19} through C_{30} using samples that had received as many as 200 zone passes. The study removed an anomaly in the relation of melting point to number of carbon atoms in the homologous series.

Organic compounds are multitudinous and notoriously impure. I think small-batch zone refining will make a major contribution in establishing the true properties of such compounds. Some recent accomplishments are noteworthy. Zone refining showed that the objectionable odor always associated with skatole (a constituent of feces) was due to impurities. Similarly, the insecticide lindane lost its musty odor after zone refining. Ortho-nitrophenol, like many similar compounds, had been thought to be self-oxidizing on exposure to air. It has now been shown that the zone-refined compound does not so oxidize.



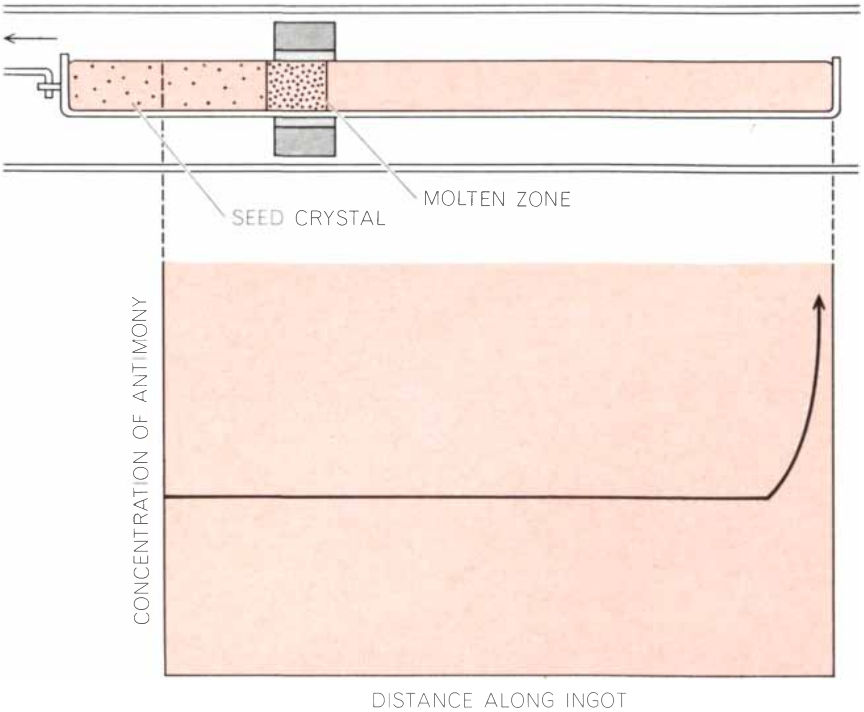
ZONE-LEVELING APPARATUS is used to distribute a uniform amount of a desirable impurity throughout a previously purified ingot of germanium. The concentration of such impurities is typically about one part in 10^7. The distribution is accomplished by one slow traverse of the heating element. This photograph was also made at Western Electric.



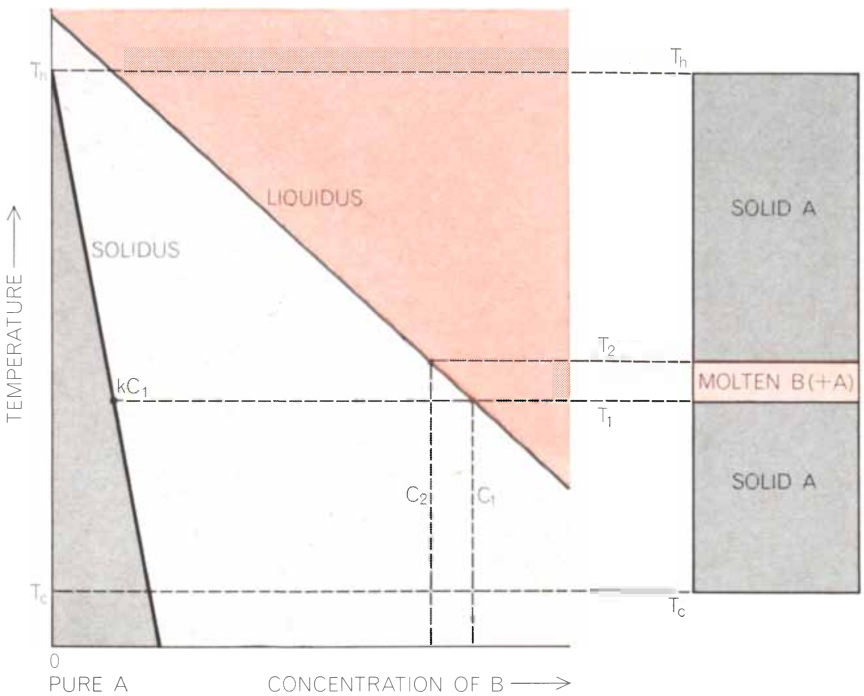
MICROSCALE ZONE REFINER for purifying milligram quantities of organic compounds was built by Hermann Schildknecht and H. Vetter at Erlangen University. It compresses some 40 molten and solid zones in a length of about six centimeters. The heaters and coolers are copper coils connected to an insulated heat source (*top*) and a heat sink (*bottom*).

Chemists, with the exception of Schildknecht and a few others, have shown surprisingly little imagination in the design of zone refining apparatus. Most of their zone refiners, as described in the literature, have long zone lengths and long interzone spacings. Recently Charles E. Miller, J. D. Hunt and I developed a zone refiner for chemical compounds that goes a long way toward eliminating these deficiencies. We call it a rotation-convection refiner [*see illustration on page 62*]. The zones are about .6 centimeter long, 2.5 centimeters in diameter and about two centimeters apart. The close spacing is achieved by having cooling water pass between a series of loose-fitting brass rings and the surface of the glass tube containing the sample. Surface tension confines the water to the space between ring and tube. The regions between the rings are heated by single loops of resistance wire. Slow rotation of the sample tube produces alternate molten and solid zones whose interfaces are practically flat and perpendicular to the surface of the tube.

Thus far I have discussed zone refining as a batch process. For purifying commercial quantities of organic compounds I believe large-scale batch and also *continuous* zone refiners will become commercial. Three different continuous methods have been conceived and worked on experimentally. In a continuous zone refiner impure feed-liquid enters somewhere near the middle of the apparatus, while purified product leaves at one end and concentrated waste leaves at the other end. These flows of feed, product and waste have to be su-



ZONE-LEVELING PRINCIPLE was thought of by the author about a dozen years before he conceived of zone refining. The ingot to be leveled rests in a "boat" (*top*) of fused silica. At the left of the ingot is a seed crystal, placed in the desired orientation, together with a measured amount of a solute, such as antimony, that has a very low distribution coefficient ($k \sim .005$). The boat is pulled slowly through a heating coil. The curve (*bottom*) shows how antimony is distributed uniformly throughout most of an ingot of germanium.



TEMPERATURE-GRADIENT ZONE MELTING, as the name implies, depends on a temperature gradient to move a zone of molten material through a solid matrix. In the simplest case a layer of *B* is sandwiched between two blocks of solid *A*. The temperature range is below the melting point of *A* but above the melting point of liquid solutions of *B* containing *A*. Thus *B* begins to dissolve some *A* at both interfaces. Solution of *A* at the cooler interface ceases at T_1 but continues at the warmer (T_2) interface. Diffusion then carries *A* from the richer (warmer) to the leaner (cooler) interface. As a result a layer of *A* containing concentration kC_1 of *B* finally freezes. In this way the molten zone climbs steadily.

perimposed on the movements of the molten zones that provide the purification.

The final variation of zone melting that I shall describe in detail is fascinating, to my mind, because it must be happening all the time in nature and conceivably, over aeons, could lead to profound geologic segregation effects. Because it depends simply on the presence of a temperature gradient, it is known as temperature-gradient zone melting. As practiced in the laboratory it differs from other zone melting methods in the relatively small size of the molten zones, in the manner of moving the zones and in the amount of solute in the zones. The zones are usually very small: sheets, wires or dots whose smallest dimension is of the order of thousandths of an inch. The zones have a high solute content, which means that they remain liquid well below the melting point of the solid through which they travel. Finally, the zones are made to move not by a traveling heat source (although this is possible) but by a stationary temperature gradient impressed across the entire charge.

These features have led to unusual applications that include fabrication of junction transistors of unusual form, joining of solid bodies with a solder that is then caused to migrate out of the joint, purifying and cleaning, measuring the diffusivity of liquids and measuring rates of dissolution and freezing. Beyond this, understanding of temperature-gradient zone melting has made technical people aware that it is a widespread phenomenon and that it must occur, often unrecognized, in many laboratory experiments, whenever a temperature gradient is present.

The phenomenon is most easily understood by examining a simple case. Imagine a system in which a thin layer of solid *B*, regarded as the solute, is sandwiched between two blocks of solid *A*, the solvent [*see bottom illustration at left*]. The sandwich is now placed in a temperature gradient so that the temperature of *B* falls somewhere between the two extremes. The temperature must be high enough to form a liquid solution of *B* containing *A* but not so high as to melt the blocks of *A*.

When the process is started, *B* immediately begins to dissolve some *A* at both interfaces, forming a liquid layer. As a result the concentration of *B* in the layer is reduced. At some point the concentration of *A* in the layer becomes high enough to cause the solution to freeze at the interface nearest the cooler end of the gradient. At the hotter interface, Foxboro engineers select A-B hot molded potentiometers

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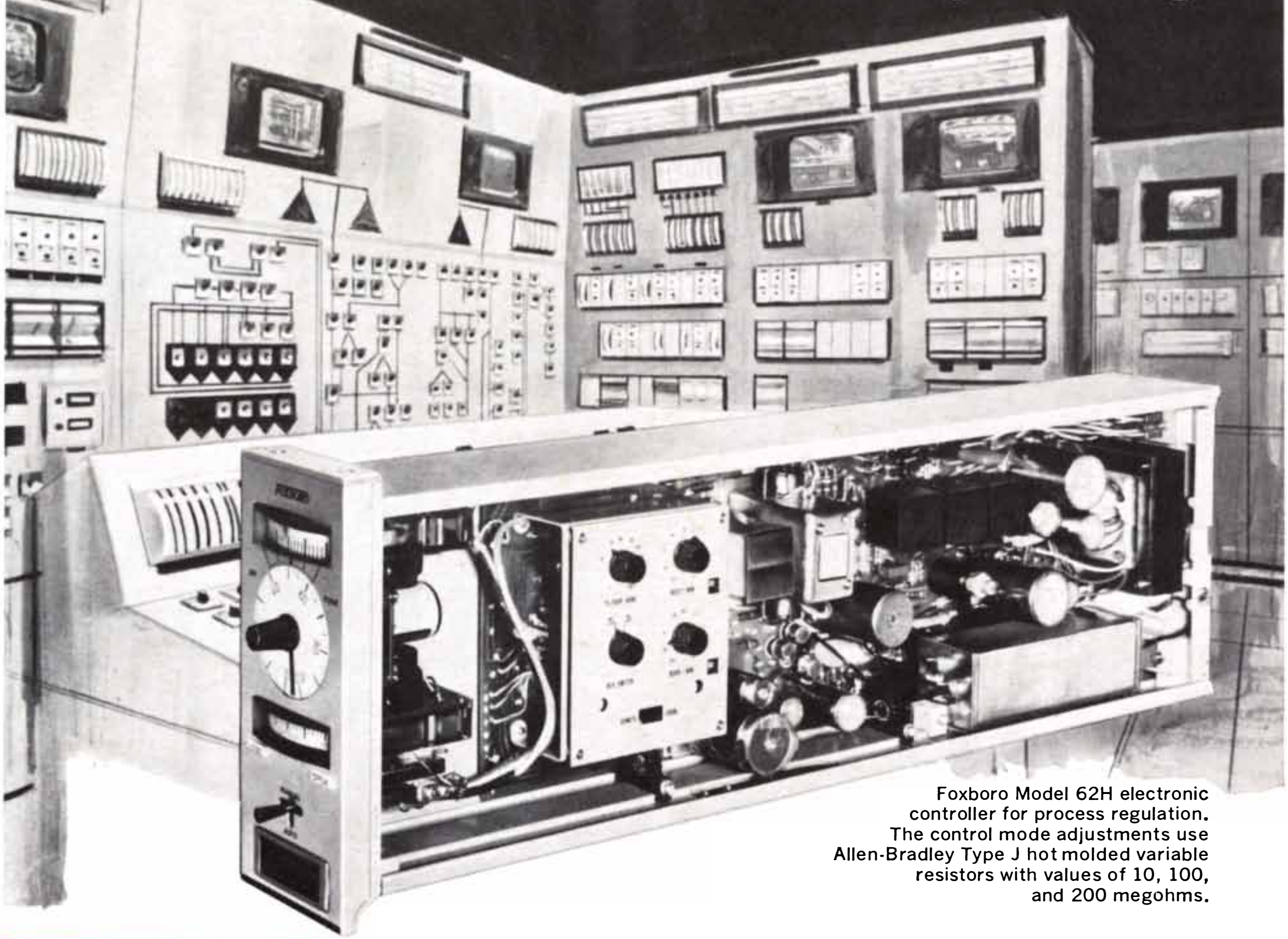
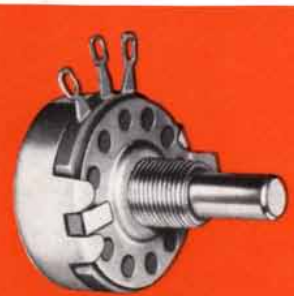


Foxboro Model 62H electronic controller for process regulation. The control mode adjustments use Allen-Bradley Type J hot molded variable resistors with values of 10, 100, and 200 megohms.



A-B Type J hot molded variable resistor rated 2.25 watts @ 70°C. Available in single, dual, and triple units. Standard total resistance values from 50 ohms to 5 megohms. Special resistance values and tapers can be supplied.

Widely used throughout the process industries, the Foxboro Model 62H Universal Controller is a highly dependable precision instrument. During the years of painstaking development, Allen-Bradley engineers worked closely with Foxboro to provide a potentiometer having unusually high resistance values, which would provide the precise performance required.

Allen-Bradley Type J potentiometers were the answer. They have a solid hot molded resistance track which is produced by an exclusive A-B molding technique that assures extremely long operating life. Accelerated tests—exceeding 100,000 revolutions—show very slight resistance change. Control is smooth at all times with adjustment approaching infinite resolution. There are none of the abrupt turn-to-turn resistance variations inherent in wirewound controls. Furthermore, Allen-Bradley Type J potentiometers are—for all practical purposes—noninductive, permitting their use throughout the frequency spectrum.

Whether your particular circuit design can be best satisfied with one of the millions of standard Type J variations or whether it calls for unusual resistance characteristics, it will pay you to look first to A-B Type J potentiometers. Their more than 25-year history of providing superior performance is your guarantee of complete satisfaction. For full details, please write for Technical Bulletin 5200: Allen-Bradley Co., 1204 South Third Street, Milwaukee, Wisconsin 53204. In Canada: Allen-Bradley Canada Limited. Export Office: 630 Third Avenue, New York, N. Y., U.S.A. 10017.

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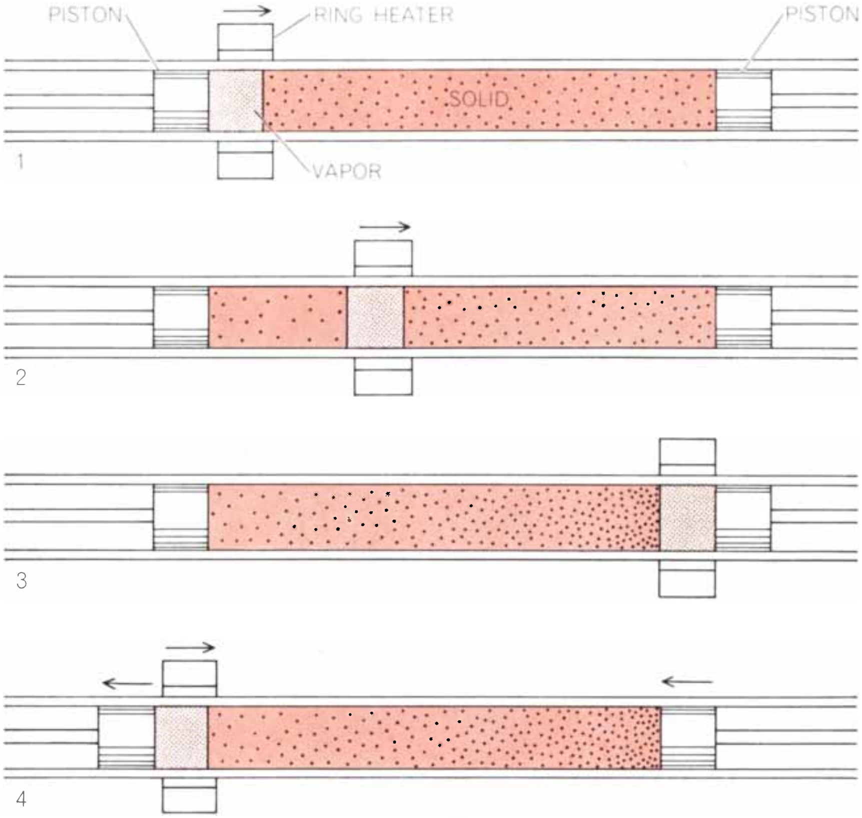


SOLID-VAPOR ZONE REFINING is one of several variations of the zoning technique. The charge is held in a tube between movable end pistons. At the start (*1*) a void is created at the left and the heater begins moving to the right. The material vaporized by the heater resolidifies to the left, behind it (*2*). When the heater reaches the right end of the tube (*3*), it is quickly moved back to the left. Simultaneously (*4*) the two pistons are moved to the left to create a new void at the left and to fill the void at the right. The process is then repeated.

meanwhile, *A* continues to dissolve in the layer. Thus within the layer a concentration gradient of *A* is created: the highest concentration near the warmer interface and the lowest near the cooler interface. The net effect is that the molten layer migrates through the block from the cooler end to the warmer end of the temperature gradient, leaving behind a solid in which the concentration of *B* is usually small.

One potentially widespread use of temperature-gradient zone melting is the removal of particles or droplets of an unwanted impurity that have become trapped during the growth of a crystal or the freezing of an alloy. If the crystal or alloy is placed in a temperature gradient, and if the temperature is high enough to cause the impurity particles to form tiny liquid droplets by dissolving the matrix, the droplets will migrate to the hotter surface, where they can be removed, thereby cleaning the main crystal.

A most useful twist of this idea was recently exploited by my colleague Richard S. Wagner. He used the method to clean the droplets rather than the matrix. He was studying the undercooling of droplets of gold-silicon alloy, which rested on the upper surface of a silicon crystal. He wanted to see how far a really clean sample of this alloy could be undercooled below its equilibrium freezing temperature. In spite of all precautions, there were always microscopic insoluble particles in the droplets that nucleated crystal growth and prevented substantial undercooling. Wagner succeeded in cleaning the droplets by applying a temperature gradient parallel to the crystal face, causing the droplets to migrate along the surface and leave the particles behind. Only then were consistent—and very large—undercoolings obtained.

Other Kinds of Zoning

So far I have discussed only those forms of zone refining that use the liquid-to-solid transformation, that is, melting and freezing. There are other useful transformations to which the zoning principle can be applied. Thus it is possible to use solid-solid zoning, solid-vapor zoning and liquid-vapor zoning.

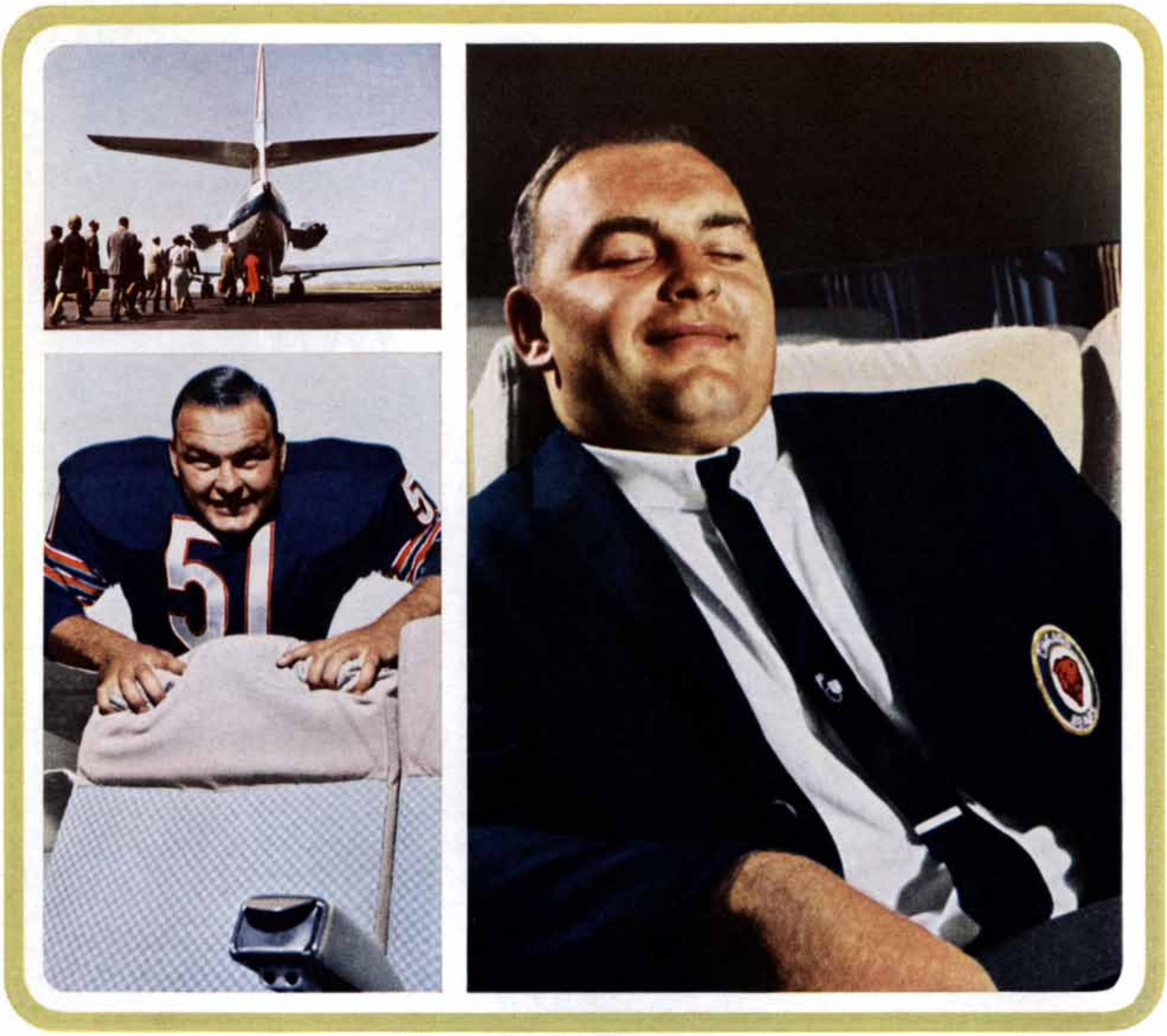
The first was demonstrated for a mixture of lithium sulfate and silver sulfate by A. Lundén and his co-workers in Sweden. This technique exploits the fact that solid solutions of two substances often show a tendency to segregate in different proportions at different temperatures. The drawback to this method is that diffusion in solids tends to be slow.

Solid-vapor zoning was introduced by Leonard R. Weisberg and Fred D. Rosi of the Radio Corporation of America to purify arsenic. In this technique a solid ingot is vaporized and solidified in zone fashion [*see illustration at left*]. By further perfecting the technique Gilbert J. Sloan of E. I. du Pont de Nemours & Co. has obtained pure tetracene from a charge containing about 30 different impurities.

The third of these unusual techniques, liquid-vapor zoning, sounds like ordinary distillation but isn't. Although to my knowledge it has not yet been demonstrated in a practical apparatus, I have diagrammed and described a hypothetical system in the second edition of my book *Zone Melting*. Liquid-vapor zoning would employ vapor zones of high diffusivity separated by liquid zones of low diffusivity. In ordinary distillation, diffusivity is high in both liquid and vapor.

There are many other variations of zone melting—some in use, some potentially useful, all interesting. I cannot describe them all in this article. To quote from my first paper on the subject in 1952: "Possibly the most significant feature of zone melting is its flexibility. The charge may be regarded as a medium, and the molten zone as a distributor of solutes in the medium.... An operator can produce a large variety of useful distributions of solute in the medium. Among the tools at his disposal are the arrangement of the starting charge, and the size, number, and direction of travel of the molten zones."

To end on a personal note, if I may, I regard the conception and development of zone melting as an exciting scientific advance. And I cannot help being saddened to hear it occasionally referred to as simply a technical innovation that was mysteriously evoked by the need for transistor-grade germanium and silicon. I regard zone melting as elegant both in its simplicity and in its surprising complexity. I also regard it to this day as a wonderful adventure, filled with surprise and joy.



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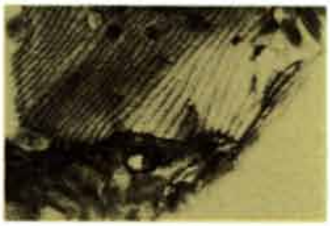
Cryogenic containers. To supercold cryogenic fluids, nearly every environment is a hot, cruel world. Vital in space missions as fuel and synthetic atmosphere sources, cryogens such as liquid hydrogen, nitrogen, oxygen and fluorine quickly vaporize without adequate protection. On the ground, they are threatened by atmospheric heat. During ascent, they must be shielded from aerodynamic heating. In orbit, they are attacked by solar radiation, albedo heat from planets, heat from electronic gear and, for the coldest, even the relative heat of less-cold cryogens.

Responding to the challenge of protecting cryogens, Lockheed launched an integrated storage systems program that furthered several technologies: The state-of-the-art in fabricating lightweight, leak-proof aluminum pressure vessels was advanced. Highly efficient, easily applied multifoil insulation systems were developed. Low-heat-leak fiberglass and titanium tank support systems were devised. And techniques using solidified cryogens to cool heat-generating electronic gear were developed. Result: the first cryogenic storage systems effective enough for long-term space missions, operating up to a month with minimal fluid losses. And with Lockheed's more recent developments—systems now are possible that can protect cryogens for a year and longer.

Thermal-mechanical strengthening of metals. Lockheed scientists, working to improve high-temperature characteristics of materials, recently have opened the door to a new family of advanced-capability metals. By applying fundamental principles of physical and mechanical metallurgy to metal processing operations, rational bases for altering metal structure were devised.



Thermal-mechanically treated molybdenum-base alloy under stress at 2,400° F, showing columbium carbide particles within stable dislocation network. Magnified 168,000 times.

Investigators found that the number and arrangement of a metal's crystalline lattice defects can be controlled effectively through certain thermal and mechanical treatments. They also found that these treatments influence the nature and distribution of foreign particles dispersed within the metal. So, since a metal's mechanical properties are governed by interactions between lattice defects and foreign particles, control of these variables can control a metal's properties. Thus, with carefully applied treatments—in all stages of development from raw materials through finished products—the nature and sequence of interactions can be guided to desired end results.

Metals currently being studied include molybdenum, titanium, stainless steel and columbium. Lockheed scientists have demonstrated that the structural integrity of these metals at temperatures in the 2,000°F to 3,000°F range can be significantly enhanced with treatment. Such improved metals soon may find application in heat shields, propulsion systems and gas turbine engine components.

Hot-operable reentry structures. During atmospheric reentry, most vehicle surfaces reach searing temperatures between 1,000°F and 2,500°F. Nose areas and leading edges often rise as high as 5,000°F. With the present practice of using aluminum and other ordinary airframe structural materials for reentry bodies, protection from such heat by complex, costly cooling and ablation systems is required. But Lockheed is exploring a way to eliminate the need for these systems.

This method takes advantage of the fact that, when heated by aerodynamic convection, material surfaces reach definite equilibrium temperature ranges where they expel heat by radiation about as fast as they pick it up. And the higher surface temperatures get, the more effective this cooling phenomenon becomes. So Lockheed's answer simply is to use structural materials that can be operated hot. These retain their strength at high temperatures, relying solely on the cooling effect of thermal radiation to survive intense reentry heat.

Materials now under study at Lockheed can carry loads at temperatures from 1,500°F to 5,000°F. Current tests involve vehicle structures made of super alloys such as René 41 and Haynes 25, protectively coated refractory metals such as columbium and tantalum, and other materials such as graphites and ceramics. These hot-operable structures may offer potential advantages in cost, lightness, simplicity and reusability.

Protective coatings. Traveling at hypersonic speeds within the upper atmosphere generates enough heat—upwards of 2,500°F—to rule out the use of many materials commonly found in airframes. They simply would melt. For metals with higher melting points, rapid oxidation becomes the great enemy, quickly destroying any exposed surfaces.

One means of combating hypersonic oxidation is protective coatings. Made mostly of ceramic bases about 3/1000 of an inch thick, these form an impervious barrier between metal and atmosphere, permitting the use of structural concepts that can be operated hot. Ideally, coatings must not react with either their environment or the metals they cover. They must adhere tightly and not contain even minute holes or fissures.

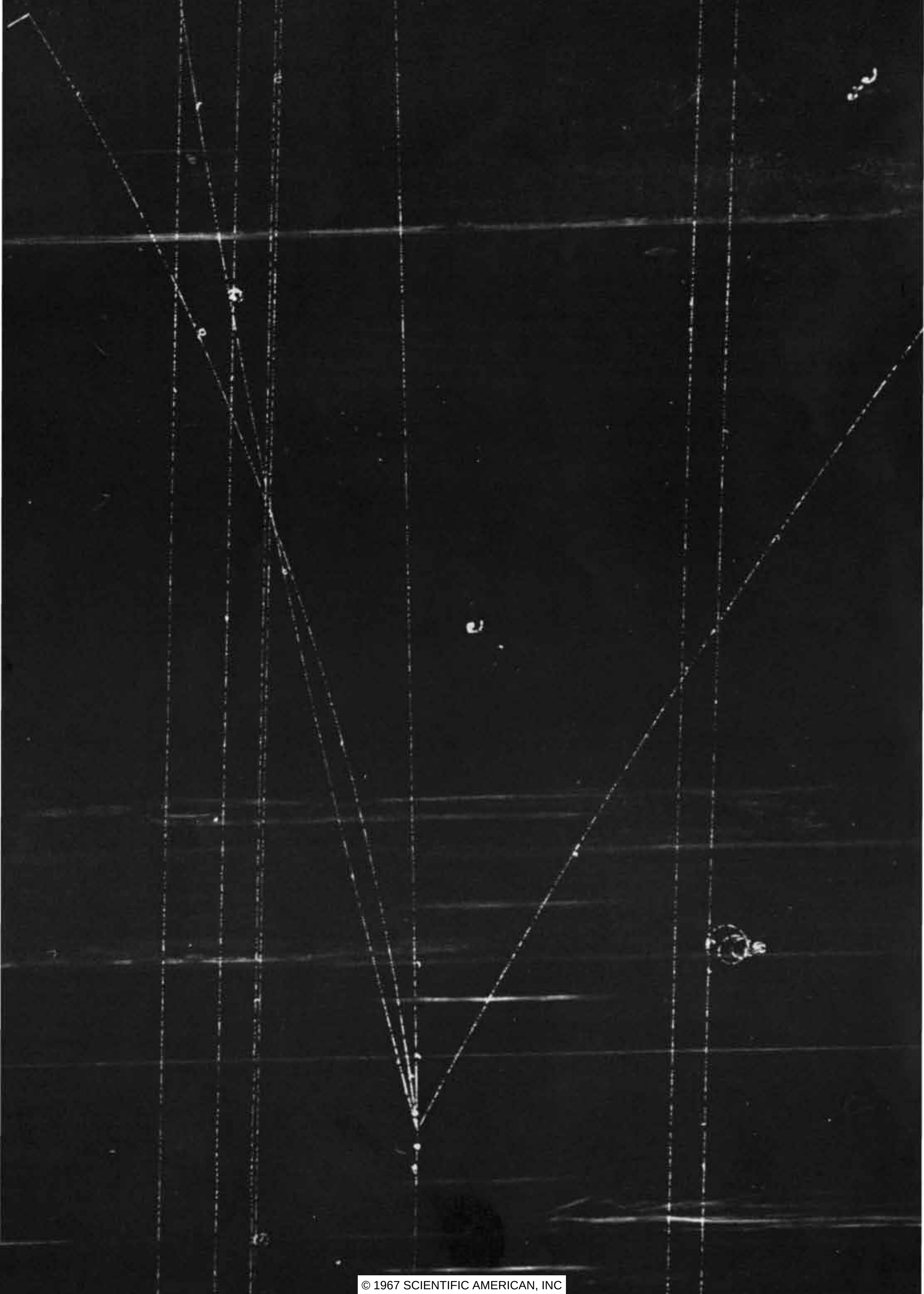
No coatings presently meet all these requirements. However, working in cooperation with other corporations and the U.S. Air Force, Lockheed is carrying on extensive test and evaluation programs that are significantly advancing coating technology state-of-the-art. Recent developments have produced coating systems that are effective for up to 100 hours for certain applications.

Composites for heat shields. A recent breakthrough in materials for hardened heat shields will help ballistic missiles penetrate harsh environments ranging from the shock of radiation to fireball traverse.

Lockheed has developed basic methods of producing composite materials possessing both thermal efficiency and structural strength superior to former state-of-the-art approaches. These are based on winding and inorganically bonding various types of filaments such as carbon, silica and graphite.

The principal advantage of these composites is that they can be tailored to function in different environments. By a gradual transition from one type of filament on the surface to another in the mid-position to yet another on the inside, optimized characteristics for particular missions can be obtained.

The activities described here are only a few of Lockheed's current R&D projects in materials. If you are an engineer or scientist interested in this field of work, Lockheed invites your inquiry. Write K. R. Kiddoo, Lockheed Aircraft Corporation, Burbank, California. An equal opportunity employer.



High-Energy Scattering

Most of what physicists know about the properties of the fundamental particles of matter is inferred from experiments in which two such particles are made to collide and the scattered products are studied

by Vernon D. Barger and David B. Cline

Of the structural components of matter that are known to modern physics, only the largest molecules can be viewed more or less directly in the form of images produced by the electron microscope. The size and properties of the smaller entities (atoms, nuclei and fundamental particles) must be determined by indirect experimental techniques. In a sense the study of fundamental particles is based on only one experiment, albeit an experiment on which there have been almost countless variations. This is the scattering experiment, in which two particles are made to collide and the results of the collision are examined. Sometimes the particles scatter from each other in much the same way that two billiard balls would, that is, the two particles emerge from the collision unchanged. In other cases complex transmutations occur in which the colliding particles disappear and other fundamental particles are simultaneously produced.

$$\pi^- + p \longrightarrow \begin{cases} \pi^- + p \\ \pi^0 + n \\ \pi^- + \pi^0 + p \\ \pi^- + \pi^- + \pi^+ + p \\ K^0 + \Lambda^0 \\ K^+ + \Sigma^- \\ \pi^- + K^+ + \Lambda^0 \end{cases}$$

HIGH-ENERGY COLLISION between a fast-moving negative pion, or pi meson, and a stationary proton is shown at the bottom of the photograph on the opposite page. The photograph was made in a large bubble chamber at the Brookhaven National Laboratory. The possible products of such a collision are indicated in the chart above. Besides pions (π) and protons (p), these products can include various combinations of neutrons (n), K mesons (K), lambda particles (Λ) or sigma particles (Σ). The one possible elastic collision (in which the incident particles emerge unchanged) is listed first. The rest are inelastic collisions. The superscript signs denote whether the particle is charged or neutral. Neutral particles do not leave tracks in the bubble chamber.

Two goals motivate the study of such phenomena. One is the search for even more basic constituents of the particles that are now considered fundamental. The other is a better understanding of the forces that control the behavior and interactions of the fundamental particles. Such an understanding would not merely help to complete the physicist's picture of the nature of the universe; it should also lead to an answer to the question of the ultimate divisibility of matter.

An elaborate technology has evolved in the past 10 years for the creation and study of the subnuclear constituents of matter. A typical chain of events leading to the production of fundamental particles in large quantity is illustrated on the next two pages. First, an abundant supply of protons is obtained by heating hydrogen gas to a temperature at which the hydrogen nuclei, which are simply individual protons, become free of the electrons. Since protons are positively charged, an electric field will cause a proton to accelerate in a straight line, whereas a magnetic field will cause a moving proton to travel in a circle. By combining electric and magnetic fields, protons can be accelerated in a circular path to very high energies. Modern accelerators operating on this principle can give a proton about 30 times the energy it has at rest. (The rest energy and rest mass of a particle are related by the Einstein principle $E = mc^2$. In the commonly used units of particle physics the energy of a single proton at rest is about a billion electron volts.)

Once the protons are moving in the accelerator with very high energy, say 30 billion electron volts, they are directed toward a target, which can be a chunk of some ordinary metal. When the beam of protons strikes the front of the target, all the known fundamental particles are produced and emerge from the back of the target with a wide spectrum of energies. One of the most common particles produced is the pion, or pi meson.

On the average, four or five pions are knocked out of the metal target by each colliding proton. Some of the pions are positively charged, some are negatively charged and others are electrically neutral. Except for charge, the positive, negative and neutral pions have nearly the same physical properties. The positive or negative pions are now deflected toward a second target. It is at this second target that the scattering of pions with other fundamental particles can be studied.

The second target is often a cylinder, some three feet in diameter and two feet deep, filled with liquid hydrogen at its boiling temperature (27 degrees centigrade above absolute zero). The liquid hydrogen can be regarded as consisting of free protons. When a charged pion moves through the chamber, heat released by the motion of the particle causes the liquid hydrogen to boil, forming a row of bubbles; such a target is called a bubble chamber. Even though the pion is incredibly small and completely invisible, the bubbles provide a means of indirectly observing its path.

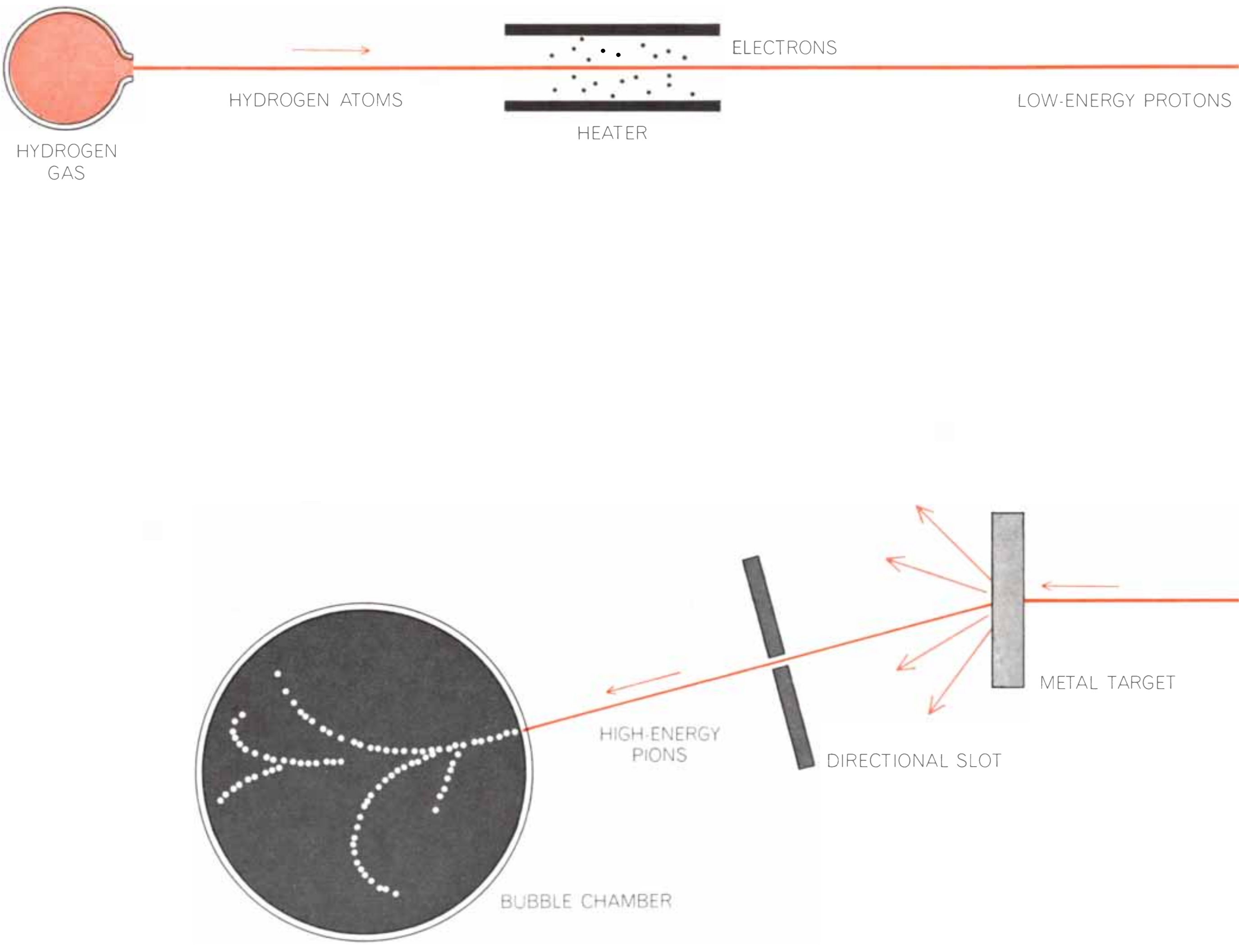
When a moving pion strikes a proton in the chamber, the charged particles that are scattered are apparent as thin lines of bubbles. Shortly after the collision a camera on the bubble chamber records the "event" by making a photograph of this pattern of bubbles [*see illustration on page 76*]. The charged particles emerging from the collision travel in curved paths, because of the magnetic field that is applied to the bubble chamber. The degree of curvature indicates the momentum of the particle. In the course of a typical experiment a total of hundreds of thousands of pictures are taken in order to obtain a few thousand events of a particular type. With these photographs in hand the physicist can begin his study of a particular particle interaction.

Certain general conservation laws that are well known from other branches of physical science also apply in particle physics. The analyses of scattering events make the assumption that energy, momentum and electric charge are conserved. For example, the law of the conservation of energy implies that the total energy of the incoming particles is equal to the total energy of the outgoing particles. In addition to electric charge, fundamental particles possess another type of charge, called baryonic charge, which is also absolutely conserved: the sum of the incoming baryonic charges equals the sum of the outgoing baryonic charges. The baryonic charge of the proton (or neutron) is +1, whereas for a pion it is 0.

The physicist's faith in the conservation of baryonic charge is strengthened by the fact that no reaction has ever been observed in which the outgoing particles had a sum of baryonic charge different from that of the incoming particles. Armed with such empirical conservation laws, the experimenter is in a position to categorize and study the multitude of processes that occur when high-energy pions strike protons inside the bubble chamber.

Once the general conservation laws of physics have been verified as holding for high-energy collisions of fundamental particles, physicists can with assurance move on to the question of the mechanisms that govern the reactions: What forces come into play in these violent collisions, and what causes the rearrangements that take place between or within the particles? The suggested answers to these questions are related in an essential way to the internal structure of the particles. In order to discuss these matters further we turn to some fundamental theoretical ideas that provide the framework within which physicists study the collisions and the structure of the particles.

The generally accepted principles underlying modern theoretical physics suggest that interactions of fundamental



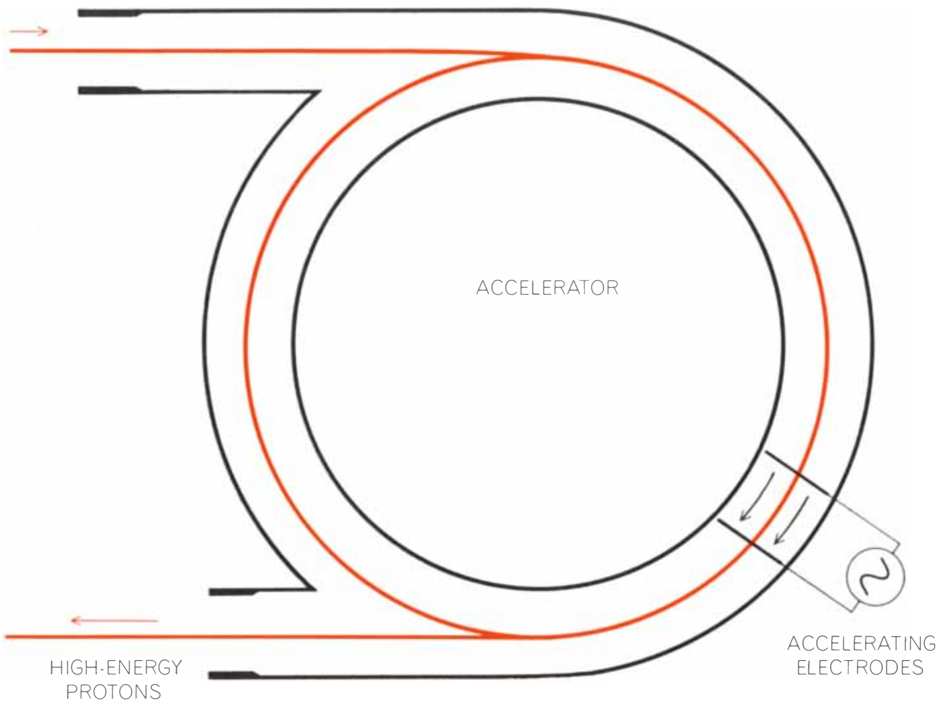
TYPICAL CHAIN OF EVENTS in a high-energy scattering experiment is shown schematically on these two pages. Low-energy protons (on the order of a billion electron volts) are obtained from hydrogen gas by heating the gas in order to remove the electrons. The protons then enter an accelerator, where they come under the combined influence of a magnetic field, which causes them to move in a circular path, and an electric field, which increases their velocity. After they have been accelerated to an energy of about 30 bilparticles can be treated as if the particles were composites of other fundamental particles. For instance, the proton can be considered to be a composite state of a neutron and a positive pion. The spontaneous dissociation of a proton into a positive pion and a neutron is never observed as a bubble-chamber event. Such an event would violate the conservation of energy and momentum. (In order to see that this dissociation violates energy conservation, consider the initial proton to be at rest. The energy of a particle at rest is given by its rest mass. Since the sum of the masses of the neutron and pion is greater than the rest mass of the proton, the dissociation cannot conserve energy.)

Almost all conceivable theories require that pions also exist in "virtual" states with masses different from the rest mass of the "real" pion observed in the laboratory. These virtual pions can be emitted by the proton without violating the conservation of energy and momentum. Unlike real pions, however, they cannot travel very far from the proton and cannot make tracks in the bubble chamber. In this way of thinking the mass of the pion takes on a continuous range of values.

The existence of virtual pions is required to explain certain characteristic properties of the fundamental particles. Just as molecules, atoms and nuclei have finite size, so do the fundamental particles. In the case of the proton, this finite size is attributed in part to a cloud of virtual pions that are constantly being emitted and reabsorbed. The size and the detailed structure of the proton is thereby related to the existence of virtual pions.

Inasmuch as virtual pions cannot be directly observed, all our information about them is inferred from the study of scattering processes. A collision between a proton and a neutron can be described in terms of a two-stage process involving a virtual pion [*see top illustration on page 82*]. The incoming proton dissociates into the outgoing neutron and a virtual pion. Before the virtual pion can be reabsorbed by the proton it is absorbed by the incoming neutron to form the outgoing proton. In this description of the collision of the proton and neutron, energy and momentum are conserved at each stage. The virtual pion can be considered the agent that transmits energy and momentum. In addition to energy and momentum conservation, all the other conservation laws are required to hold for each event.

Not only pions but all particles are assumed to exist in virtual states as well as real states. The concept of virtual particles is at the core of our understanding of the interactions of fundamental particles.



lion electron volts (BeV) the protons are directed at a metal target, where they interact to create many new particles. Beyond the target, certain types of particles are selected and transported to the bubble chamber, where their interactions are observed by means of lines of bubbles that are formed in the liquid hydrogen by the passage of charged particles.

Although all scattering processes must satisfy the basic laws of the conservation of energy and momentum, there is a fundamental distinction between the scattering of macroscopic objects and the scattering of subatomic particles. In the scattering of billiard balls the initial directions and velocities of the balls completely determine their final configuration [*see bottom illustration on page 82*]. In the scattering of subatomic particles, on the other hand, a particular configuration of the particles after collision can never be predicted with complete certainty. This uncertainty is a consequence of the wavelike nature of subatomic particles and is described by the theory of quantum mechanics. In the domain of subatomic size the theory makes predictions only regarding the probability of a certain configuration of the particles after collision. Thus the theories that predict the scattering of fundamental particles cannot be tested with the observation of a single collision (as for example with a single bubble-chamber photograph) but must be tested through the observation of a large number of scattering events.

In collisions involving fundamental particles the incoming particles may retain their original identity after the collision (in which case the process is called elastic scattering) or the incident particles may be transmuted into two different outgoing particles as a result of the collision (inelastic scattering). Simple examples of these two basic types of collision in the scattering of pions (π) and protons (p) are $\pi^- + p \rightarrow \pi^- + p$

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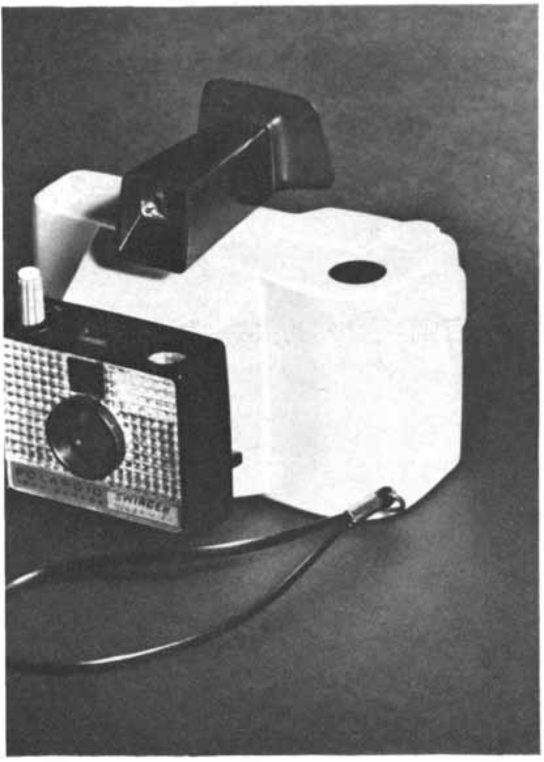

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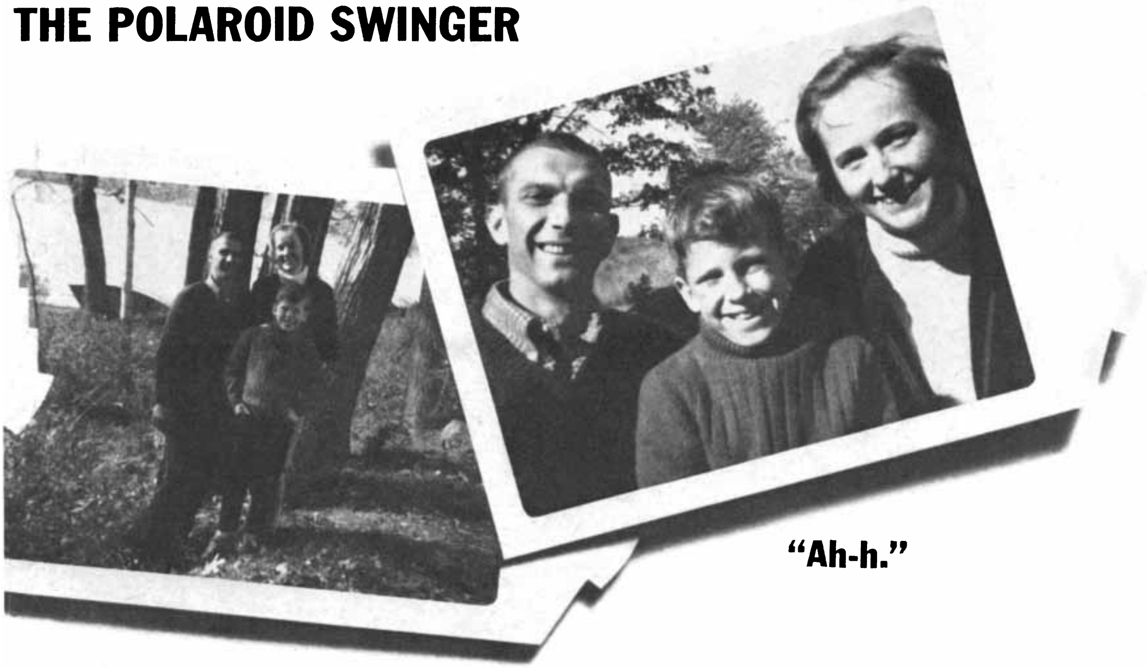
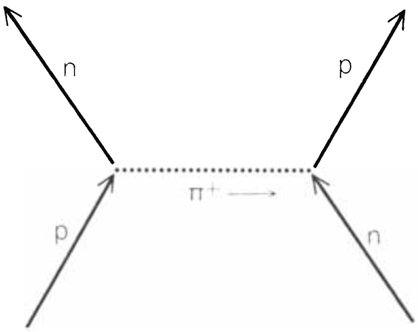


"Ah-h."

"That background's not right."

*suggested list price



SCATTERING of a proton and a neutron can be interpreted in terms of a two-stage process involving the exchange of a "virtual" π^+ meson, which can be considered the agent that transmits energy and momentum. First the incoming proton dissociates into the outgoing neutron and a virtual pion. Then the virtual pion is absorbed by the incoming neutron to form the outgoing proton. For simplicity the two particles are regarded as moving toward each other before the collision occurs, although in practice one of the particles is initially at rest.

(an elastic event) and $\pi^- + p \rightarrow \pi^0 + n$ (an inelastic event). We defer for the moment the discussion of inelastic events with many particles in the final state. A valid theory of fundamental particles must correctly predict the probability that an elastic or an inelastic event will occur. These predictions will generally depend on the energies of the particles and the directions in which the particles scatter. Qualitative predictions for scattering events can sometimes be deduced from a knowledge of the kinds of virtual particle that can mediate the scattering process.

The scattering of fundamental particles can in fact be used to probe the characteristics of virtual-particle exchange. In an interaction involving two particles the two extremes are forward scattering and backward scattering. In forward scattering the momentum and the direction of each particle after the collision is nearly the same as it was before the collision. In backward scattering the direction of the motion of each of the incoming particles is nearly reversed by the collision. One of the outstanding advances in the description of particle scattering has been the interpretation of forward scattering in terms of the exchange of a virtual meson (for example a virtual pion) and the interpretation of backward scattering in terms of the exchange of a virtual baryon (for example a virtual proton or a virtual neutron).

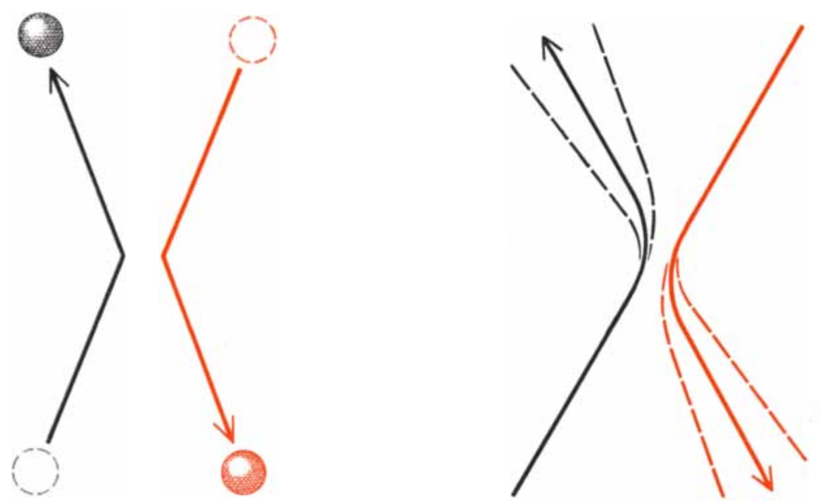
When a virtual-pion exchange mediates a reaction, the particles scatter in a characteristic grazing fashion [*see illustration on opposite page*]. In this case the reaction $p + n \rightarrow p + n$ can proceed by means of the exchange of a virtual neutral pion. Since the incident proton and neutron are much more massive than the comparatively light virtual pion, the collision can be compared to two pickup trucks passing in opposite directions with a bag of sand being tossed from one truck to the other. The overwhelming probability is that the incident proton (or neutron) will be only slightly deflected from the incident direction. The angle of deflection between the outgoing proton and the incoming proton (called the scattering angle) is therefore very small for this virtual-pion exchange process. When the probability of scattering is plotted against the angle of scattering for a typical virtual-meson exchange process at high energy, it becomes evident that the probability that the two incident particles will scatter is appreciable only for forward, or small, angles of scattering [*see illustration on page 84*].

Backward scattering presents a more intriguing situation, involving the exchange of virtual neutrons or protons. As a simple example, consider the reaction $\pi^+ + p \rightarrow p + \pi^+$, which can proceed through the exchange of a virtual neutron. In this reaction the final proton comes out in the same direction as the incoming pion. In other words, the scattering angle between the initial proton and the final proton is quite large. With virtual-neutron exchange the probability that the incident π^+ and the proton will scatter from each other is appreciable only for these backward, or large, scattering angles. A bubble-chamber photograph showing such a backward-scattering event is shown on page 89.

The concept of virtual particles is subject to direct experimental test. After measuring the paths of the particles on the bubble-chamber photographs of a specific scattering process, the physicist makes a plot of the number of events observed at each value of the scattering angle. By comparing these experimental plots with the predicted probability distributions he can determine whether the scattering is due to virtual-meson exchange or virtual-baryon exchange. In some reactions clusters of events are observed at both forward and backward angles, indicating the presence of both virtual mesons and virtual baryons in the region of interaction between the scattered particles. The events from some other reactions exhibit only a forward peaking or a backward peaking of the events. The presence or absence of such peaks can be directly interpreted in terms of the existence or nonexistence of virtual particles that can be exchanged. But since a real particle is in turn associated with each virtual particle, the forward or backward peaks give direct information about the existence or nonexistence of real particles. This qualitative theoretical association of forward and backward peaks with particles that are found in nature appears to be

a

b



BILLIARD BALLS AND SUBATOMIC PARTICLES scatter differently. In the scattering of billiard balls (*left*) the directions and velocities of the balls can be predicted from their initial directions and velocities. For a single collision of subatomic particles (*right*), the directions and velocities of the outgoing particles cannot be predicted except to the extent that the final configuration of the particles must always conserve energy and momentum.

in remarkably good agreement with experiment.

Among the more interesting early discoveries about the nature of fundamental particles was the necessity to associate with each particle an intrinsic spin. In a rather superficial sense a fundamental particle behaves like a spinning top. The basic property that spinning tops and fundamental particles have in common is angular momentum. For a spinning top the angular momentum is related in a simple way to the dimensions of the top and its number of revolutions per second. Although a fundamental particle cannot be viewed simply as an object rotating about an axis, it is still proper to associate an intrinsic spin angular momentum with each particle. This intrinsic spin for particles was discovered long ago, and the measurement of intrinsic spins is commonplace in the course of experimental research. Still, an intuitive picture for the origin of the intrinsic spin of fundamental particles does not exist.

The observed intrinsic spin angular momentum of a given fundamental particle always has the same magnitude. Furthermore, the intrinsic spins of different particles can always be expressed as multiples of a basic unit of spin, in much the same way that the charges of particles are always multiples of a basic unit of charge (namely the charge of a proton). Using this basic unit for spin, the neutron and the proton each have spin 1/2 and the pion has spin 0. In fact, all fundamental particles can be divided into two classes: fermions, particles with half-spins (1/2, 3/2, 5/2, 7/2 and so on) and bosons, particles with whole spins (0, 1, 2, 3 and so on).

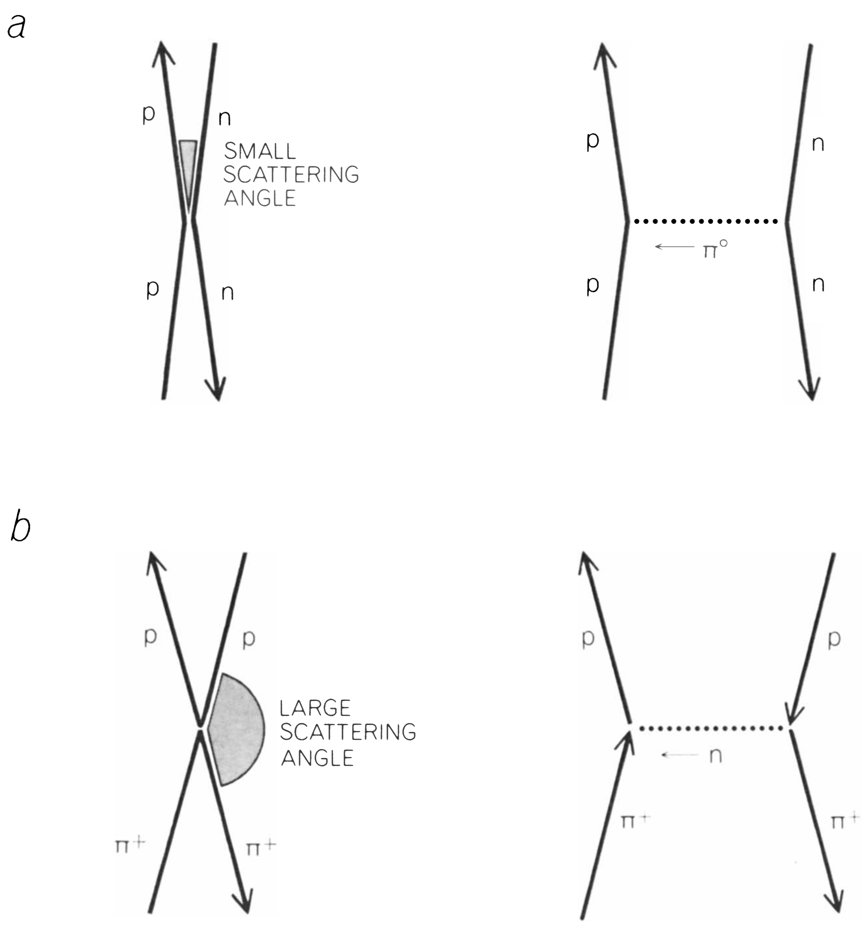
The question naturally arises of whether spin angular momentum can take on continuous values for virtual particles in much the same way that the mass becomes continuous for virtual particles. This speculation has been the subject of intense investigation for the past several years and has led to exciting insights into the probable behavior of fundamental-particle interactions at high energy.

The discovery of a theory that focuses on both continuous spin and continuous mass for virtual particles has revolutionized our concepts about fundamental particles. This new theory implies a profound connection between the spin and the mass of a particle whether the particle is real or virtual. A macroscopic analogy of such a connection between spin and mass can be found in a spinning top. As the top speeds up it gains energy (and hence mass by the Einstein principle) through rotation; at the same time the top gains spin angular momentum. Thus the effective mass of the top increases as the spin increases. A similar connection, although one of a much subtler nature, exists between the effective mass and the spin of both real and virtual particles. This is shown graphically on page 90. Because of the tremendous amount of information contained in this illustration (which is usually called a Chew-Frautschi diagram) it has come to play a central role in studies of fundamental particles.

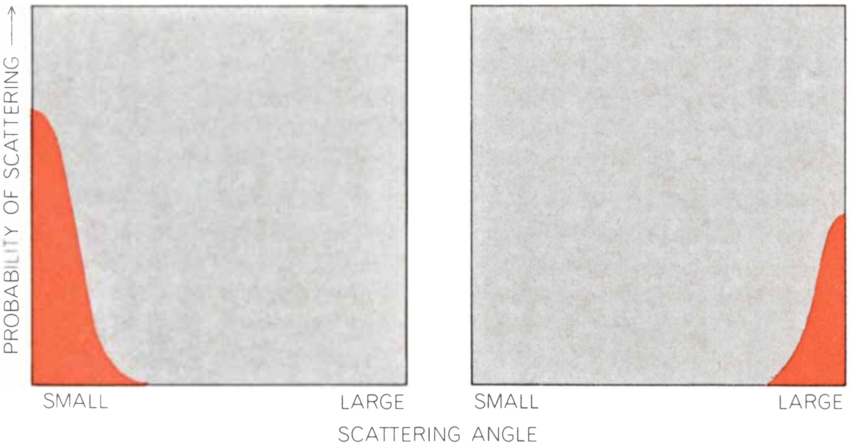
The diagram represents a generalization of the previously discussed connection between real particles and virtual particles. As a concrete example, consider the diagram that represents the real and the virtual states of the proton. Any point on the diagonal line (which is called the Regge trajectory of the proton) represents the proton in a certain state. The state of the proton that is observed in the bubble-chamber photographs has a spin of 1/2 and a mass equivalent to about a billion electron volts, and hence it appears as a point with these coordinates on the trajectory.

An intriguing aspect of this plot of spin v. mass involves the points on the trajectory lying to the right of the observed proton. As the trajectory continues to rise it crosses other positive half-multiples of spin (for example 3/2, 5/2, 7/2, 9/2 and so on), which are also permissible spins for observable fermions. Actually, according to the theory only particles with spins 1/2, 5/2, 9/2 and so on are expected to exist for the proton family. Thus in addition to a proton with spin 1/2 a chain of particles with progressively increasing masses and spins is predicted. A striking confirmation of these predictions has been the recent experimental observation of several low-lying members of such particle families.

The number of fundamental particles discovered each year has been increasing at a prodigious rate. Already a great many of these particles have been classified in families similar to those discussed



SCATTERING ANGLE is related to the type of virtual particle that is exchanged between two interacting real particles. In a collision between a proton and a neutron (*top*), which is mediated by the exchange of a virtual π^0 meson, the scattering angle tends to be small (forward scattering). In a collision between a π^+ meson and a proton (*bottom*), which is mediated by the exchange of a virtual neutron, the angle tends to be large (backward scattering).



PROBABILITY OF SCATTERING depends generally on whether the exchanged virtual particle is a meson (for instance a pion) or a baryon (for instance a neutron or a proton). The exchange of a virtual meson gives rise to a high probability of scattering only for small scattering angles (*graph at left*), whereas the exchange of a virtual baryon gives rise to a high probability of scattering only for large scattering angles (*graph at right*). Some scattering processes (for example $\pi^+ + p \rightarrow \pi^+ + p$) exhibit both forward and backward scattering peaks, indicating that both virtual mesons and virtual baryons are exchanged.

above. In fact, if the Regge trajectories continue to rise, there is an exciting possibility that the number of particles within a given family may actually be infinite! As far as we know, each member of a family is equally fundamental. Therefore there is nothing special about the proton except that it happens to have the lowest mass and spin on the proton chain. Just as several centuries ago the idea that the earth was the center of the universe had to be abandoned, so the idea that the proton occupies a special position among the fundamental particles must now be reconsidered.

The theory also predicts that mesons occur in families. Thus the pion with spin 0 is expected to be the lowest member of a chain of pions with spins 0, 2, 4 and so on. A number of recently discovered mesons appear to be members of such families.

Within a single family there is the prospect of large numbers of fundamental particles. In keeping with our preceding discussion of scattering processes, each of these fundamental particles can also exist in a virtual state and thereby mediate scattering processes. Fortunately the extension of the virtual-particle concept to include virtual spin simulates the effect of exchanging in a scattering process all the individual members of a family. In essence all the particles of one family are considered as a single entity with virtual spin and virtual mass and this entity is exchanged in a scattering process. In the Chew-Frautschi plot of the proton family any point on the trajectory to the left of zero virtual mass represents the complete proton family in a particular state that mediates a scattering process.

The belief in particles with virtual spin has received considerable substantiation from the success of the theory in classifying the multitude of fundamental particles as members of families. Even more direct evidence bearing on the idea of virtual spin is derived from studies of the scattering of fundamental particles at high energy.

The probability of scattering of two particles depends both on the angle through which they scatter and the total energy of the incoming particles. As we have mentioned, the dependence of the probability of scattering on the angle is directly associated with the type of virtual particle that can be exchanged; the exchange of a virtual meson causes forward scattering, whereas the exchange of a virtual baryon causes backward scattering.

There is other important information that can be extracted from an analysis of the scattering data. In particular one can make use of the dependence of the scattering on the total energy of the incoming particles. For a fixed value of the square of the mass of the virtual particle being exchanged, the theory predicts that the virtual spin of the exchanged particle determines the rate at which the probability of scattering decreases with increasing energy. The lower the value of the virtual spin, the less the incident particles should scatter as the energy increases. Therefore, given the value of the virtual spin from a Regge trajectory, the theory makes definite predictions about the energy dependence of the probability of scattering. These predictions are subject to direct experimental test and are borne out remarkably by the data on fundamental-particle scattering at high energy.

In this theory of particles with virtual mass and virtual spin, the description of the scattering processes and the classification of the observed particles into families are treated on an equal footing. The common link that relates these two seemingly different aspects of fundamental particles is the Regge trajectory. The overall self-consistency of the theoretical connection between scattering and families of particles supports the hypothesis that fundamental particles are composites of each other and that no finer subdivisions of matter than the fundamental particles exist in nature. It should perhaps be pointed out, however, that this interpretation is not shared by all physicists. We shall mention later an alternate viewpoint concerning possible building blocks of matter even more basic than the fundamental particles.

The prospect of a systematic explanation of all experimental data on two-particle scattering processes at high energy in terms of a limited number of virtual-particle exchanges presents an exciting challenge to physicists. Of equal interest is the explanation of an interference phenomenon that has recently been observed in the scattering of fundamental particles at energies lower than those considered in the foregoing discussion. This interference phenomenon occurs as fluctuations in the probability of scattering when the energy of the incident particles decreases. Such interference effects are well known in atomic and nuclear physics. An example of this effect in the scattering of fundamental particles is shown in the illustration at top left on page 91. The gray curve represents the probability of scattering expected from the virtual-particle exchange. At high energy the virtual-particle exchange accounts for all the scattering. As the energy of the incident particles is decreased, however, a new phenomenon occurs and the observed scattering probability is no longer adequately explained by the contribution of virtual-particle exchange.

We have interpreted this interference phenomenon as an interplay between two different physical scattering mechanisms, one of which is virtual-particle exchange. The other mechanism, which

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The men handling it are veteran tanker captains. The ship is a scale model of a giant super-tanker now being built. The water is an eight-acre training "sea" complete with waves, channels, moorings and piers. They're all part of a remarkable Marine Research and Training Center that Jersey opened last July in France.

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becomes important only at lower energies, has to do with the formation of new particle "states." A simple way to visualize this mechanism is to regard the incoming particles as balls of putty. When the particles collide, they stick together for a very short time, during which the system can be regarded as a "resonance" particle [see "Resonance Particles," by R. D. Hill; SCIENTIFIC AMERICAN, January, 1963]. Then the resonance particle splits apart into the final particles. A diagram illustrating the formation and disintegration of such a resonance state is shown at top right on page 91. In general all particles must participate as intermediate resonance particles in the scattering process as long as the basic conservation laws are obeyed.

As the plot of scattering probability shows, the two different scattering mechanisms can result in constructive or destructive interference. The positions of the maxima and minima are directly correlated with the masses of the resonance particles that participate in the scattering. These resonance particles are members of families such as the one shown in the Chew-Frautschi diagram.

The study of these interference patterns shows great promise for unraveling the mass spectra of the fundamental particles and for cataloguing the detailed characteristics of the resonance particles. Furthermore, the successful explanation of complicated interference patterns of this kind gives us considerable hope of establishing the intimate relation between scattering and the particles' mass spectra.

When an incident pion strikes a proton in the bubble chamber, the number of particles that can be produced is limited only by the total energy of the incoming pion and the stationary proton. Thus at very high incident energy a large number of different types of final state are possible. For example, a few of the numerous energetically allowed reactions in a π^-p collision are given in the chart on page 77.

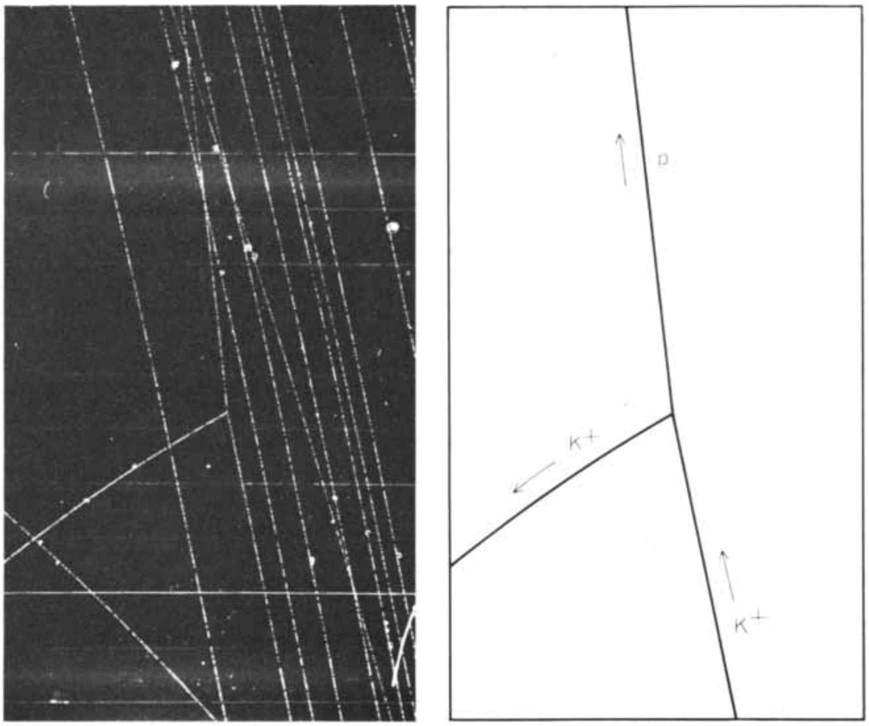
As a π^- meson moves through a bubble chamber there is a probability that it passes through without interacting and a probability that it collides with a proton, producing one of the many possible final states. Obviously the sum of these two probabilities is 1. The probability that the π^- meson interacts is called the total scattering probability.

Because of the great complexity of reactions with three or more particles in the final state, present theory is not capable of making definite predictions about these reactions individually. A simple piece of data pertaining to the multitude of processes with many outgoing particles, however, is the total scattering probability. A basic theorem of scattering theory, known as the optical theorem, relates the total scattering probability to forward elastic scattering. Thus a theoretical prediction for forward elastic scattering on the basis of virtual-meson exchange also determines the total scattering probability. When a meson trajectory is exchanged, the value of the virtual spin for the trajectory corresponding to zero virtual mass controls the behavior of the forward elastic scattering probability and hence the total scattering probability. As a result the virtual spin of the exchanged trajectory fixes the energy dependence of the total scattering probability.

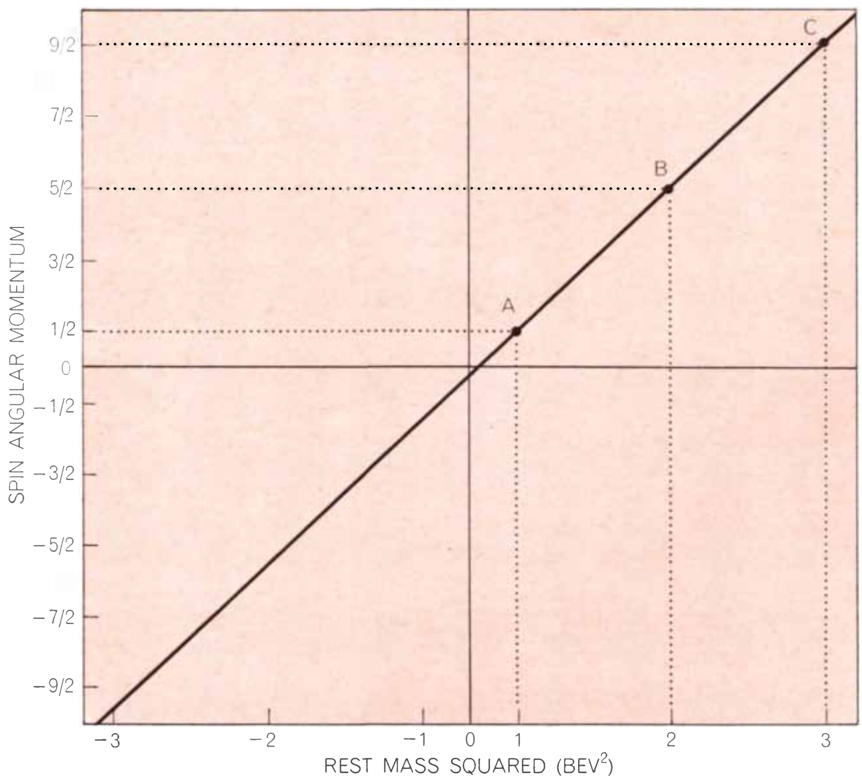
Recently some very accurate experimental measurements have been made for the total scattering probability of π^-p collisions and π^+p collisions up to the highest obtainable accelerator energy (26 billion electron volts, or BeV) at the Brookhaven National Laboratory. The energy dependence of these findings has been successfully described by the virtual-meson-exchange hypothesis. The data show two fascinating trends.

The first of these trends is an indication that the total scattering probability may tend to have a constant value at the highest energies. Judging from the enormous number of multiparticle final states that become energetically feasible as the energy increases, we might have intuitively expected that the total scattering probability would increase instead. If the total scattering probability is actually constant at high energy, this would indicate that a meson of virtual spin 1 is being exchanged. Although there are possible assignments of recently observed mesons to a trajectory that has a virtual particle with virtual spin 1 and mass 0, no definite identification has been made as yet.

The second interesting trend apparent in the Brookhaven data is the approach to equality of the π^-p and π^+p total scattering probabilities as the energy increases. Again intuition might not have led us to this conclusion, since different final states are realizable for the two processes. The exchange of single trajectory with virtual spin 1 and virtual mass 0 predicts that the π^-p and π^+p



BACKWARD-SCATTERING EVENT is shown in the bubble-chamber photograph at left and in the corresponding map at right. The reaction is $K^+ + p \rightarrow p + K^+$. The initial proton was at rest in the bubble chamber, whereas the K^+ meson had an incident energy of 3.5 BeV. The backward-scattered K^+ meson is recognizable by the heavy density of bubbles in its track, indicating that it is moving slower than the other particles. To analyze such an event, the data on angles and momenta must first be transformed into a reference system in which the K^+ meson and the proton approach each other with equal momenta.



CHEW-FRAUTSCHI PLOT of the members of the proton family shows the connection between the spin and the mass of both real and virtual particles. The real particles that are observed in the bubble chamber are denoted by the black dots. The proton (*A*) has a spin of 1/2 and a mass at rest equivalent to 1 BeV. The observable particles of higher mass (*B*, *C*) are called recurrences and have spins of 5/2, 9/2 and so on. Any point on the diagonal line (which is called a Regge trajectory) represents a possible state of the proton family. Points on the Regge trajectory in the bottom left-hand quadrant of the diagram represent virtual states of the proton family that are involved in the mediation of scattering processes.

total scattering probabilities will become equal at ultrahigh energies.

Present experiments and theory reveal that we may be on the verge of a breakthrough in our understanding of fundamental-particle scattering. In order to explore the validity of these ideas further, it will be necessary to study the total scattering probability at higher accelerator energies. This step will most likely come with the completion of the gigantic 200-BeV accelerator in the U.S. and the 300-BeV accelerator planned in Europe. Within the next decade or so we may well have a wealth of experimental data from these machines.

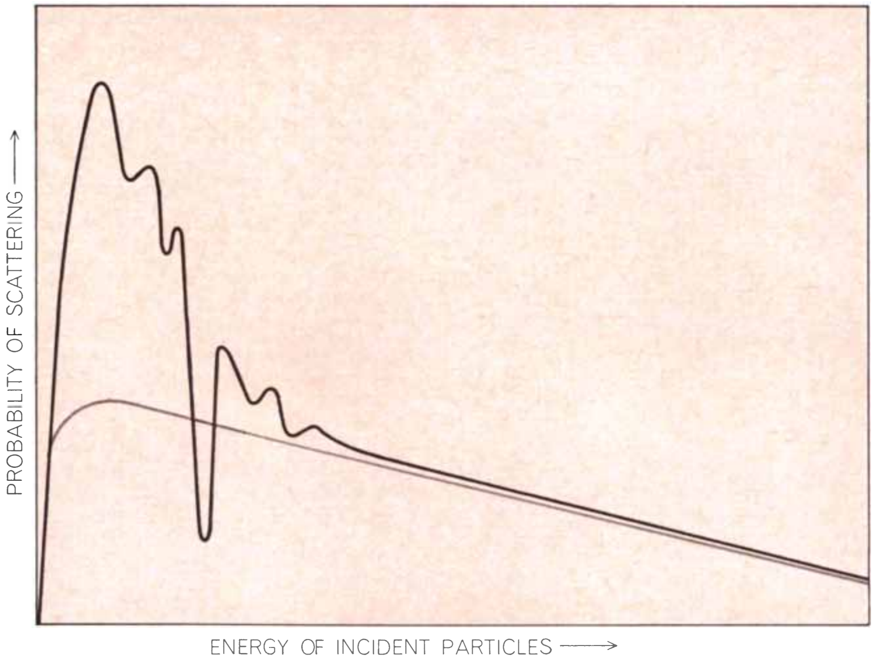
The historical development of science has depended critically on the discovery of more and more basic components of matter. At each stage of the search the known particles (molecules, atoms, nuclei, protons and so on) were thought by some to be the ultimate building blocks. Physicists are faced again with this recurring question. As might be expected, there are two schools of thought regarding the divisibility of fundamental particles into undiscovered constituents.

One of the most novel theoretical explanations has been conceived by Murray Gell-Mann and George Zweig of the California Institute of Technology, who propose to build all fundamental particles from a set of six particles, three "quarks" and three "antiquarks." Unlike any particles that have ever been discovered, the quarks or antiquarks would carry electric and baryonic charges that are a third or two-thirds of the corresponding charges of the proton. In this scheme a proton is built up of three quarks and the pion of a quark and an antiquark. Experimental physicists are actively searching for quarks in the products of high-energy collisions, but no positive evidence for their existence has been reported. If a proton really is a loosely bound system of three quarks, then the mass of the quark should be a third of the proton mass. A particle with such a small mass would, however, presumably be copiously produced with present accelerator energies. In fact, current experiments place a lower limit on the mass of the quark that is about three times the mass of the proton! As a result, in order for a proton to be composed of three such massive quarks enormous binding energies are required. Such a situation would break with the historical progression of discovery, wherein the binding energy of the composite state has always been much smaller than the mass of the composite state.

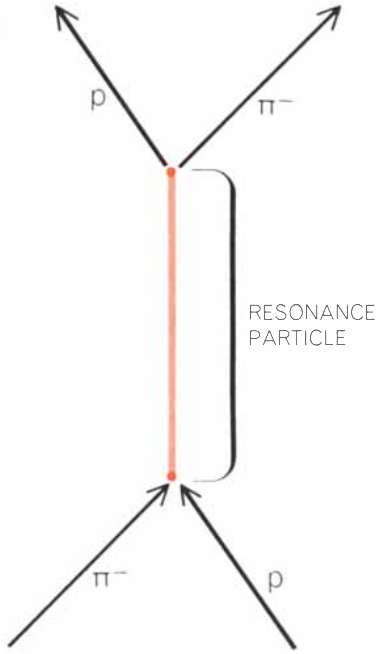
One of the interesting theoretical predictions of the quark picture pertains to the total scattering probability of fundamental particles at high energies. Forward elastic scattering in the quark picture is schematically illustrated at the bottom of the opposite page. Here the collisions of fundamental particles are given by the sum of all possible elastic collisions of two quarks or antiquarks. (Quarks and antiquarks are assumed to scatter by the same amount at high energy.) This model makes the very interesting prediction that the total scattering probability of a π^+p interaction divided by the total scattering probability of a pp collision is equal to 2/3 at very high energy. The present experimental data at high energy give a number for this ratio that is of the order of 2/3. This celebrated ratio is regarded in some circles as evidence for the quark structure of fundamental particles.

The alternate viewpoint proposes that the historical search for more basic constituents of matter has ended with the present species of fundamental particles. The complete consistency of the description of fundamental particles as composites of each other is regarded as evidence that the particles actually sustain each other. This profound philosophical concept, emphasized by Geoffrey F. Chew of the University of California at Berkeley, suggests that all fundamental particles are equally basic—a true democracy among the fundamental particles. The present evidence in favor of this viewpoint comes from two sources. First, the fact that the proton lies on a trajectory populated by many other particles suggests that the proton is no more fundamental than the other members of the proton family. A similar statement can presumably be made for meson systems. Second, the successful description of high-energy scattering in terms of observed particles makes it plausible that the exchange of such particles provides the very forces that give rise to the observed particles.

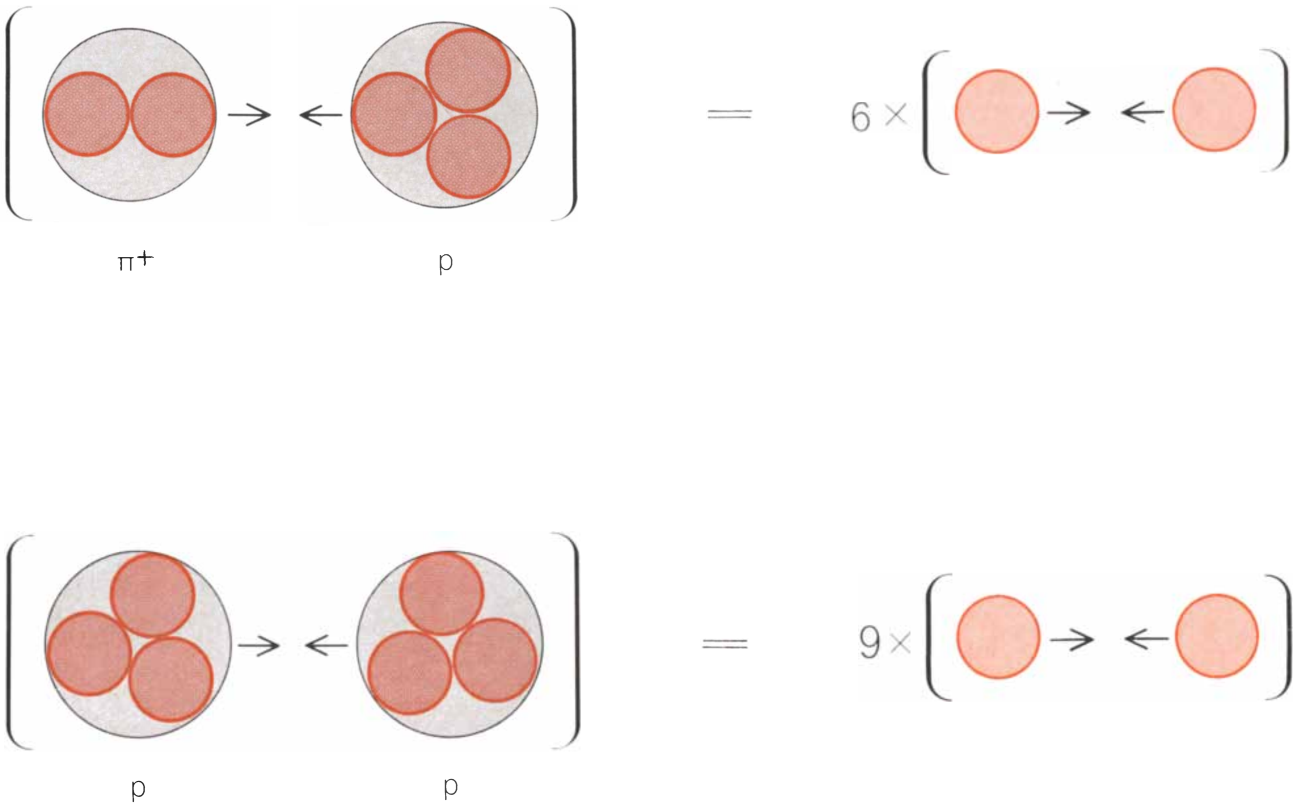
Our best hope of eventually distinguishing these two viewpoints is further study of very-high-energy scattering of fundamental particles. The great challenge of the next few decades will be to discover which route nature has taken: quarks or democracy?



INTERFERENCE PHENOMENON has recently been observed in the scattering of fundamental particles at low energies. The phenomenon appears as fluctuations in the probability of scattering (*black curve*) when the energy of the incident particles decreases. The gray curve represents the probability of scattering expected from the exchange of virtual particles; at high energies this process apparently accounts for all the scattering. The fluctuations at lower energies are believed by the authors to be caused by interplay of two factors: the exchange of virtual particles and the formation and disintegration of "resonance" particles.



RESONANCE PARTICLE is a temporary coalescence of two colliding particles. In this example of elastic $\pi^- p$ scattering the incoming pion and proton combine to form a resonance particle (*color*), which after a short time (about 10^{-23} second) disintegrates into the outgoing pion and proton.



QUARK PICTURE of the forward elastic scattering of fundamental particles is given in this highly schematic illustration. In this model the π^+ meson is assumed to be composed of a quark and an antiquark, whereas the proton consists of three quarks. The elastic scattering of two particles is thus reduced to the individual scatterings of the quark constituents. Quark-quark and quark-antiquark total scattering probabilities are assumed to be equal. The quark model predicts that the total scattering probability of a pion-proton interaction divided by the total scattering probability of a proton-proton interaction is equal to 2/3 at very high energy.

MONOCHORD, the most effective demonstration of the Pythagorean laws of proportion, consists of a single string stretched on a frame. In this print, from a 12th-century manuscript, the 11th-century theoretician Guido d'Arezzo is explaining the divisions of the string to Archbishop Theobald. The letters along the side of the instrument are the notes of the scale, beginning with gamma, or *G*, which represents the total length of the string. The pitch of a note depends on the length of string that has been left free to vibrate.

The Vibrating String of the Pythagoreans

The monochord gave rise to far more than Western musical scales. For the Greeks and those who followed them music was number, and the ratios of the scale were manifested in nature and in the arts

by E. Eugene Helm

Igor Stravinsky once observed that musical form is "far closer to mathematics than to literature—not perhaps to mathematics itself, but certainly to something like mathematical thinking and mathematical relationships." Stravinsky spoke from the viewpoint of a composer who, like many of his colleagues, has consciously made "something like mathematical thinking" an integral element of his music. This element is widely regarded as a hallmark of modern music. What is seldom appreciated, even in the musical world, is that the roots of the relation between music and mathematics extend deep into antiquity. The way in which the two were betrothed and the course the marriage has taken over the centuries make a beguiling and instructive tale.

They were plighted, these two, by the Greeks—more precisely, by the school of Pythagoras in the sixth century B.C., although their courtship certainly began, perhaps even earlier, among the Chaldeans, Egyptians, Babylonians and Chinese. During the next few centuries the Pythagoreans joined music and number irrevocably by means of a vibrating string. Whether the string was actually mounted and measured or was only described in speculative treatises and imaginatively or pedantically discussed, it has vibrated in the conscious and unconscious minds of musicians, mathematicians, philosophers, astronomers, physicists and architects ever since.

In its simplest form the basic Pythagorean doctrine relating number to music can be described as follows. Pluck a stretched string of any length and allow it to vibrate; it will sound a certain pitch. Allow only half of it to vibrate, and the pitch will rise an octave. If two-thirds of the string vibrates, the pitch will rise a fifth above the one produced by the total length. For instance, if the total length produces *C*, two-thirds of the string will produce *G*. (The interval *C-G* is called a fifth because five lines and spaces on the musical staff are traversed in going from one to the other, counting *C* and *G*.) Three-fourths of the string will yield a pitch a fourth higher than the total length (*F*, if the total yields *C*); eight-ninths, a whole step, or a second, higher (*D* if the total yields *C*), and so on. In time the fractions become more complex and the two notes represented by the resulting intervals become more dissonant if they are sounded together. The fraction for the half-step, for example, is 243/256.

The Pythagoreans used these musical facts to construct scales. Gradually the relation of the vibrating portion of a string to the entire string came to be expressed in ratios, such as 1 : 2 for the octave, 2 : 3 for the fifth and so forth. Soon it was noted that the most harmonious intervals were those with the simplest ratios. For example, 2 : 3 (the fifth) was much more harmonious than 8 : 9 (the whole step). Both the intellectual appeal of simplicity and the sensuous appeal of harmoniousness made the simple relations come to be regarded as superior to complex ones. Harmonious sounds, said the Pythagoreans, are produced by ratios expressible as whole numbers, and the simpler the ratios—the smaller the whole numbers expressing them—the more consonant the sound.

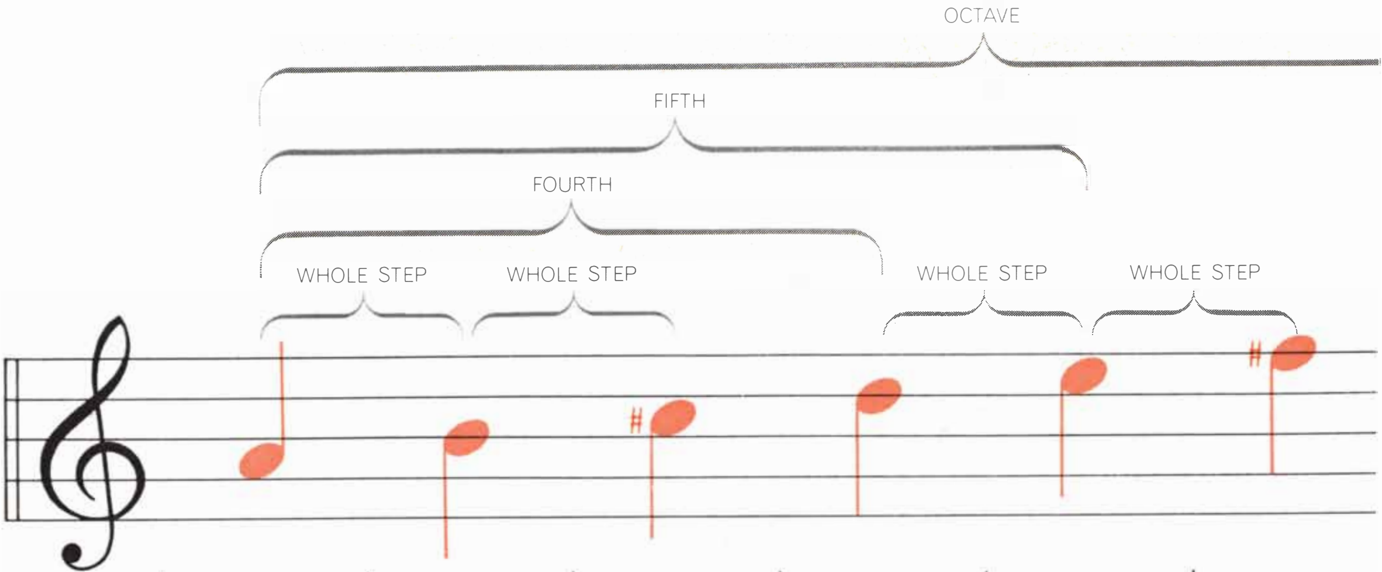
It followed from these attitudes that the octave, the fifth and the fourth were regarded as musically superior to other intervals. Indeed, since early medieval times the octave, fifth and fourth have been called the "perfect consonances." Until the end of the Middle Ages these intervals were the theoretical basis of almost all Western polyphony.

To the fascination of the Pythagoreans the same sets of numbers seemed to keep cropping up in other matters. A single order, expressible in number and ratio, evidently governed all the rhythms of nature: the four seasons, the two tides, the pendulum-like fluctuations of human affairs—in fact, all the machinery of the universe from microcosm to macrocosm. The most succinct expressions of the numbers and ratios governing the orderly events of nature seemed to be precisely those that applied also to music. It is small wonder, then, that Pythagorean thinkers came to regard music as a key to all being.

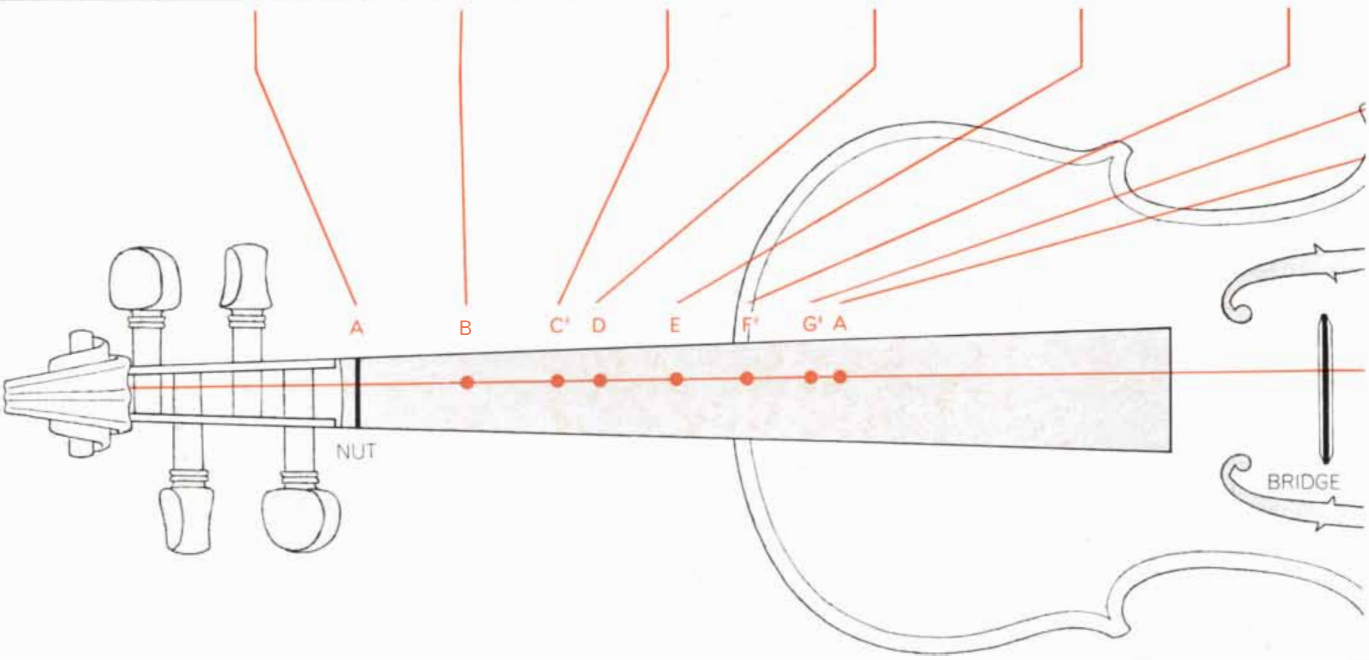
A notable example of their thinking is the myth of the "music of the spheres." The Pythagoreans believed that bodies moving in space produced sounds unheard by ordinary mortals, and that bodies moving rapidly produced sounds of higher pitch than the sounds produced by bodies moving slowly. Greek astronomy of the sixth century B.C. held that the greater the distance of a planet from the earth, the more rapidly the planet moved. Moreover, the distances between planets and the ratios between speeds of planets (relative to the earth) were both thought to be harmonically determined, that is, expressible in whole-number ratios. Therefore the sounds produced by the planets harmonized with one another.

"Music of the spheres" also meant the mathematical ordering of the physical universe: the regulation of the world by laws of musical proportion. In this sense music was mathematics. Thus it was primarily the Pythagoreans who established music as a mathematical discipline, causing it eventually to be put into the quadrivium—the standard three-year course of study in medieval universities—along with the other mathematical studies of arithmetic, geometry and astronomy.

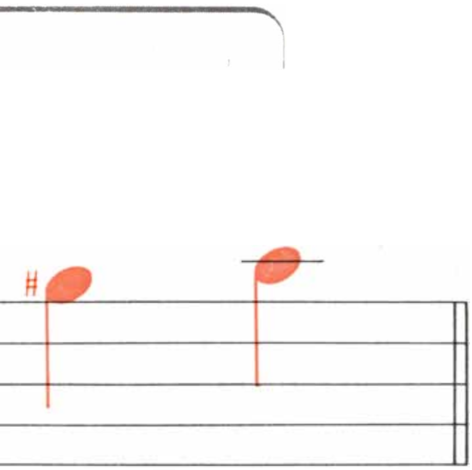
Plato, under the influence of Pythago-



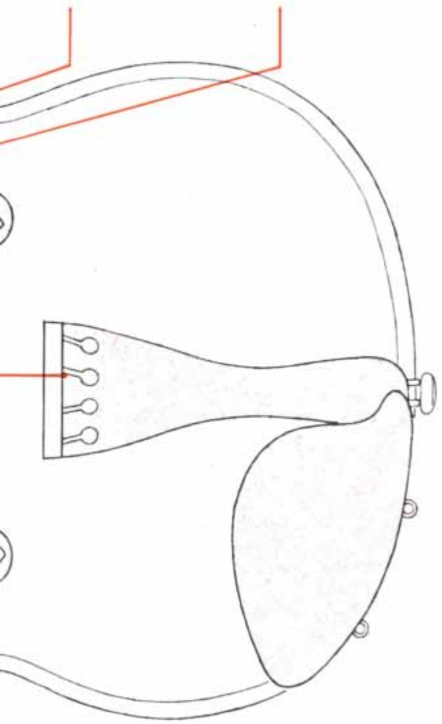
NOTE	A	B	C#	D	E	F#
FINGER POSITION	OPEN	1/9 FROM NUT TO BRIDGE	1/9 FROM B TO BRIDGE	1/4 FROM NUT TO BRIDGE	1/3 FROM NUT TO BRIDGE	1/9 FROM E TO BRIDGE
LENGTH OF STRING	1	8/9	8/9 × 8/9 = 64/81	3/4	2/3	8/9 × 2/3 = 16/27
FREQUENCY (CYCLES PER SECOND)	440	9/8 × 440 = 495	81/64 × 440 = 556.875	4/3 × 440 = 586.667	3/2 × 440 = 660	27/16 × 440 = 742.5



PYTHAGOREAN SCALE (not quite the same as the modern "equal-tempered" scale) is derived by dividing a string, as illustrated here with the *A* string of the violin. Sounding the total length from nut to bridge produces an *A*, with a frequency of 440 cycles per second. (Frequencies are a modern concept, unknown to the Pythagoreans.) Stopping the string by placing the finger 1/9 of the way from the nut to the bridge leaves 8/9 of the string open, producing a *B*, and so on. The only intervals used to construct the Py-



G♯	A
1/9 FROM F♯ TO BRIDGE	1/2 FROM NUT TO BRIDGE
8/9 × 16/27 = 128/243	1/2
243/128 × 440 = 835.312	2 × 440 = 880



thagorean scale are the octave, fifth, fourth and whole step; the other intervals, such as the third (*A* to *C*-sharp) have complex ratios that must be derived from the simpler ones.

reanism, probably did as much to raise music to this level as the Pythagoreans themselves did. He gives a description of the music of the spheres in Book X of the *Republic*. His classic view of a world created according to musical proportion appears in the *Timaeus*.

Pythagorean and Platonic doctrines of music as number and proportion and music as part of science and mathematics were passed on almost intact into the Christian era. It is no coincidence that Ptolemy, the great astronomer of the second century, was also a leading music theorist. Nor is it surprising that the medieval thinkers who followed him could hardly begin to scrutinize the universe quantitatively without first taking a long look at music.

The chief medieval transmitter of the ancients' ideas on musical proportion was Boethius, the sixth-century Roman philosopher and mathematician. He classified the proportions and helped to establish a new terminology expressing them in words: *proportio dupla* for 1 : 2, *proportio sesquialtera* for 2 : 3, *proportio sesquitertia* for 3 : 4 and so on. His name is most remembered, however, for another refinement of the old doctrines: the division of music into three types. One was *musica mundana,* the harmony of the spheres; the second was *musica humana,* the harmony of the human soul and body, and the third was *musica instrumentalis,* the actual playing and singing of music. The third category, which is now considered the main aspect of music, was in the time of Boethius regarded as the lowest of the three forms. Playing and singing were only tinny reflections of the greater harmonies embodied in the other categories. The true musician was the man who knew music as part of a celestial order; the mere performer was only a servant. As Boethius put it, the performer was "separated from music" because "physical skill obeys like a handmaid while reason rules like a mistress."

Medieval treatises on music were often slavish restatements of the old doctrines as Boethius had defined them. Philosophers and mathematicians, as well as music theorists and composers, commonly felt obliged to pay their respects to music as a traditional mathematical discipline before proceeding to more contemporary matters. Standard operating procedure seemed to be to quote respectfully from Boethius (or to steal his ideas without acknowledgment) and to include a drawing of Pythagoras striking sonorous bodies or adjusting strings of various lengths. An instrument called the monochord became widely used as a means of illustrating the ancient musical laws. This instrument, dating back to Greek times, consisted of a single string mounted on a flat surface and was provided with movable bridges and an accurate means of marking off certain lengths of the string.

Throughout the Middle Ages this speculative side of the musical art ran parallel to music making. Although folk music and the music of such practical artists as troubadours and minnesingers were relatively untouched by speculation, the all-pervading ratios and the music of the spheres were not far distant. The great monasteries, and later the cathedral schools and the universities, kept the old mathematical traditions alive and flourishing. For example, one of the writings of Pietro d'Abano, who in 1315 was Distinguished Professor of Medicine, Philosophy and Astrology at the University of Padua, was a treatise entitled "Is Musical Consonance Found in the Pulse?" Occasionally the mathematical way of thinking affected music in the most direct way. Philippe de Vitry's treatise *Ars Nova,* which dates from about 1320, presented a revolutionary system of metrical organization that inaugurated a new musical age and that had to be justified in traditional mathematical fashion. By the end of the 14th century French secular music had arrived at a degree of rhythmic complexity undreamed of by De Vitry and hardly equaled in the 20th century. (This music, incidentally, has recently been widely admired by a number of contemporary composers and avant-garde musicians.)

One would be remiss to discuss the laws of musical consonance as they applied to music alone in the Middle Ages. Musical proportions appear almost everywhere in the thought and art of medieval Europe. To St. Augustine the octave seemed to be rooted in the very being of even the most untutored man and therefore must have been implanted in man's nature by God himself as a means of conveying to human ears the meaning of redemption. To the School of Chartres in the 12th century the garbled fragment of the *Timaeus* then available had almost the stature of Holy Writ. The scholars of Chartres discovered musical proportions in the dimensions of Solomon's temple and built such proportions into their own great cathedral.

Indeed, Otto von Simson has shown in his recent book *The Gothic Cathedral* that not only the cathedral of Chartres but also nearly all the great Gothic cathedrals were conceived as "music in

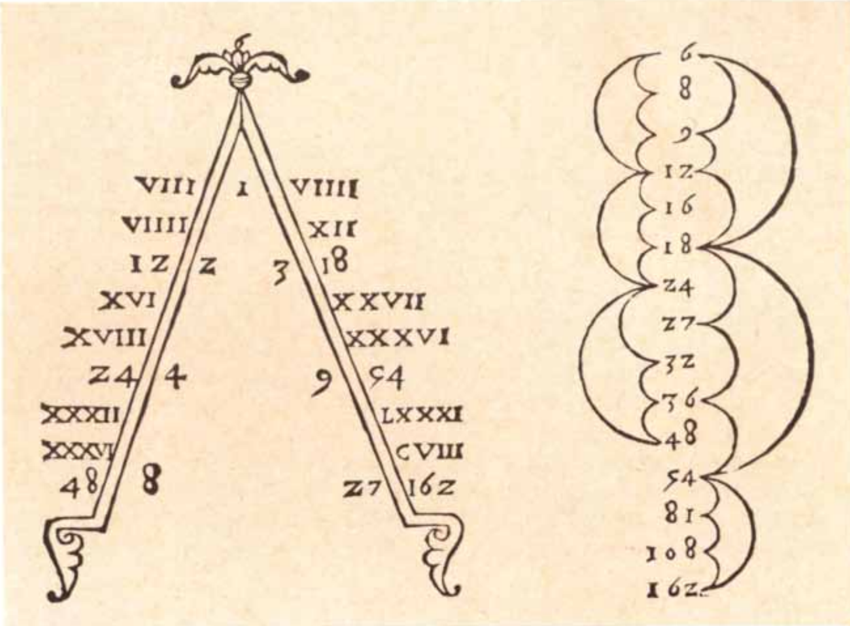
HARMONIC PROPORTIONS are demonstrated in several ways in these panels from Franchino Gafurio's *Theorica Musice* of 1492. The biblical father of music, Jubal, is shown perceiving the consonances in weighted hammers (*top left*), an insight that is usually attributed to Pythagoras. In the other panels Pythagoras is seen, with his follower Philolaus, demonstrating the tones of bells of different sizes, glasses filled to different levels, strings that are stretched by different weights and pipes of different lengths.

stone." The conception was literal as well as poetic. When proportions of 1 : 2 or 2 : 3 or 3 : 4 are found in such a building, they are not fortuitous but the result of deliberate intent. Simson argues that when they are not found literally, they are distinctly relevant to the actual proportions used.

In the Renaissance the dual character of the epoch—its imitation of antiquity on the one hand and its preoccupation with present things of the senses on the other—is nowhere better illustrated than in the attitudes of Renaissance thinkers toward the old notions of proportion. Some were contemptuous or condescending; among them were the music theorists Johannes Tinctoris, Sebastian Virdung, Martin Agricola and Vincenzo Galilei (father of Galileo). Just as many other important theorists, however, upheld the precepts of proportion; among them were Gioseffe Zarlino, Ugolino d'Orvieto, Franchino Gafori, Francesco Salinas and Marin Mersenne.

One should not regard these latter scholars and composers as mere transmitters of dogma. Each of them built important new structures on old foundations. Zarlino, for instance, went beyond the first four numbers in his classification of consonances, adding the major third (4 : 5) and minor third (5 : 6) to the Pythagorean ratios, and thus giving the theorist's sanction to the established compositional practice of treating thirds as consonances. Another example is provided by the number of Renaissance theorists and composers who applied ratios such as 3 : 2 and 4 : 3 to the *rhythmic* values of compositions (making three rhythmic units in one measure equal to two in another, for instance). In so doing they extended the ratios far beyond Pythagorean and Boethian bounds.

A second illustration of Renaissance duality can be found among its literary and architectural monuments. The music of the spheres was a stock idea among poets and writers from Chaucer to Dryden, yet by the 17th century it had lost its potency in literature. In Renaissance architecture the old Pythagorean proportions eventually underwent the same kind of dilution, but not before they had assumed a rather fantastic importance. Rudolf Wittkower has shown in his book *Architectural Principles in the Age of Humanism* that mathematical expressions of musical consonance, and the whole philosophical context in which the expressions had been presented in Pythagorean, Platonic and neo-Platonic writings, were basic to the determination of the proportions of buildings in Italy during the 15th and 16th centuries.



GEOMETRIC DIAGRAM published by the architect Francesco Giorgi in 1525 presents the proportions listed in Plato's *Timaeus*. Inside the legs of the Greek letter lambda (*inverted V at left*) are the double and triple intervals. These are multiplied by six (except for the "1") along the outside of the legs. Between them the harmonic and arithmetic means are supplied (*Roman numerals*). All the multiplied quantities are arranged in one column at right, with double (*left*) and triple (*right*) basic proportions and means indicated by arcs.

A case in point is the document in which the 16th-century Franciscan monk Francesco Giorgi recommends proportions for Santa Francesco della Vigna, a church to be built in Venice. The width of the nave, he says, should be nine paces (the square of three, which is itself the *numero primo e divino*). The length of the nave is specified as 27 paces (3 × 9). Giorgi states that the square and the cube of three contain the consonances of the universe, and that the ratio 9 : 27 represents two fundamental musical intervals, the octave and the fifth. The *cappella grande* at the far end of the nave was to be nine paces long and six paces wide (3 : 2, the fifth). The *cappella*'s length would then equal the nave's width, and other harmonic relations would obtain.

When the building was actually designed a generation later by the architect Andrea Palladio, it was done in more imaginative fashion. For example, the only really obvious case of proportionality in the building is the central façade, which—in correspondence with the width of the nave—has a width of 27 modules. But nobody really argued with Giorgi's literalness. The Doge of Venice consulted a painter, a humanist and an architect about Giorgi's recommendations, and all three approved. The painter was Titian.

Giorgi's ideas are on the verge of being too simple. The principles of proportion were actually applied, however, in sophisticated ways. Mean proportionals (those lying between the standard ratios as arithmetic and harmonic means) are found everywhere in Renaissance architectural dimensions. Moreover, builders such as Palladio and Leon Battista Alberti employed "generated" ratios. Alberti, for example, generated the ratio 4 : 9 with two ratios of 2 : 3.

The 17th century saw at least a partial continuation of the Renaissance duality of attitude toward music as ratio, although the beginnings of a general breakdown in the whole venerable structure were definitely in evidence. The chief musico-mathematical development of the century was the rise of an acoustical science based on observation. Galileo, Mersenne, Halley, Huygens, Newton and others studied actual physical sound and established principles that might have been expected to clear the air of old-style speculations about the nature and meaning of music. Even these heroes of the new scientific age regarded the ancient traditions more with affection than with ridicule. A few scientists based absolutely new ideas on the old concepts; in this group the most spectacular achievement was that of Johannes Kepler.

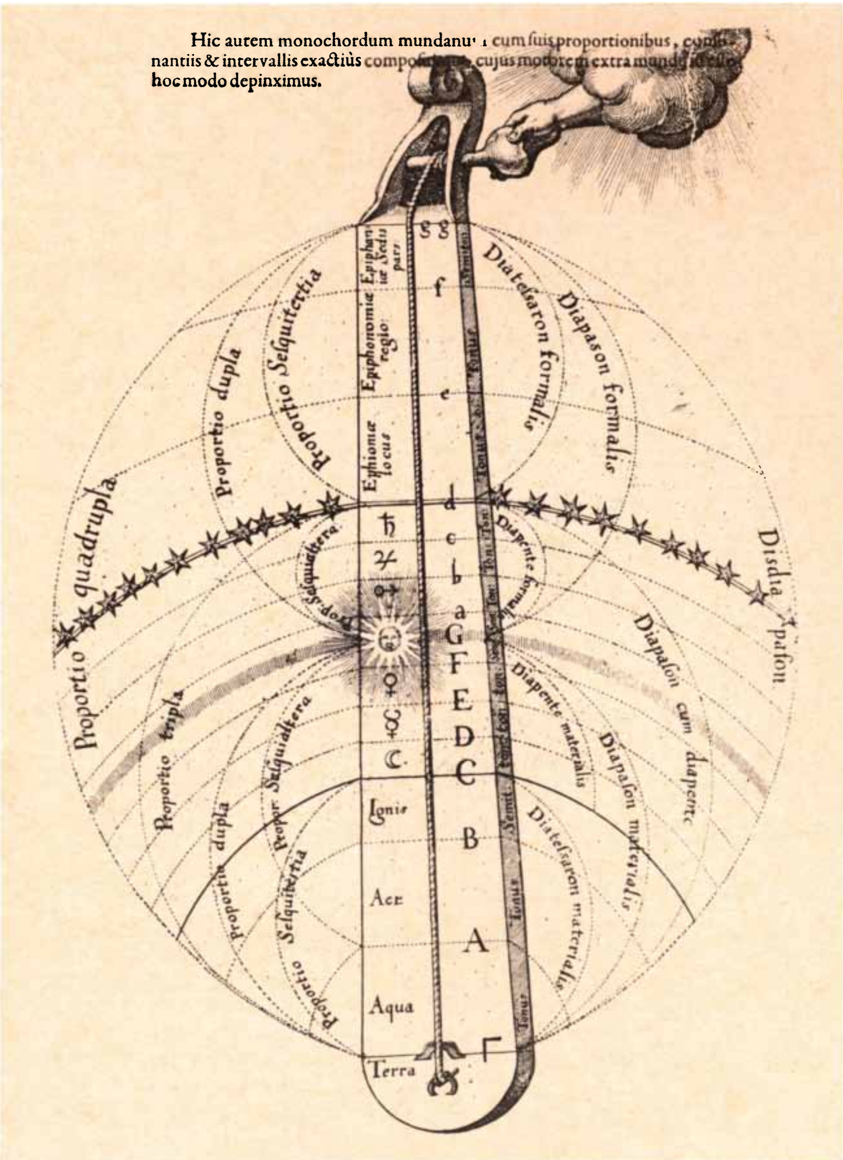
Kepler was on the one hand the

founder of physical astronomy and the thinker who placed Copernicus' church-shaking heliocentric theory on a firm mathematical foundation. On the other hand he was a mystic soaked in medieval speculation and an occasional astrologer whose lifelong view of the universe was essentially that of Pythagoras and Plato. His largest work, *De Harmonice Mundi* (*Concerning the Harmonies of the World*), published in 1619, is one of the most astonishing events in the history of ideas. It is a latter-day explanation of the music of the spheres, which Kepler believed was heard only by the Being that animates the sun. The whole basis of the treatise is Kepler's conviction that the various parts of the universe are arranged in accordance with abstract notions of the beautiful and harmonious; yet it is in this treatise that he sets forth his famous third law of planetary motion.

The law is one result of Kepler's long attempt to relate musical harmony to planetary motion and, more specifically, to find a "musically harmonious" relation between the distances of the planets from the sun. The distances vary as the planets revolve around the sun, and so Kepler's first calculations were based on the greatest and least distances. When calculations in distances failed to produce a concord, Kepler turned his attention to the angular velocities of the planets. (Velocities and distances are related, since the closer a planet approaches to the sun, the greater is its angular velocity with respect to the sun.)

Kepler associated the varying angular velocity of each planet with a musical interval, letting the two outer notes of the interval represent the greatest and least velocities. Then he put each planet's interval into a different pitch register, which was determined by the planet's average distance from the sun. Next he tried to relate the average angular velocities to the average distances from the sun. When this approach did not disclose God's harmony, Kepler substituted the period of revolution for the average angular velocity. Here he found the relation he had been seeking.

Kepler's third law is usually stated as a mathematical formula: $T^2/D^3 = K$, where T is a planet's period of revolution, D is its average distance from the sun and K is a constant. The values of T and D are known for the earth: T is one year and D is 93 million miles. Therefore K can be computed, so that one can compute any other planet's average distance from the sun if the period of revolution is known or the period of revolution if the average distance is known. The formula looks antiseptic, but like so much of mathematics it springs from the aesthetic power of natural order. Essentially it is this same aesthetic power that lies at the root of music's relation to number.



GOD'S HAND tunes the "monochord of the world" in an illustration from a book published in 1617. The classical elements and the planets appear, along with the musical ratios.

As "duality" is the word for the attitude of thinkers during and immediately after the Renaissance toward the relation of music and number, so "reconciliation" is the word for the period from 1600 to 1750. This period, the age of the Baroque, is one in which feeling seems at first to have predominated over mathematical tradition. Below the surface of Monteverdi's operas, Corelli's sonatas and Bach's fugues, however, is a continuing and fundamental respect for number as a basis of music.

The reconciliation was particularly evident in the work of the French theorist and composer Jean Philippe Rameau, who stands as perhaps the foremost theorist in the history of Western music. In the first half of the 18th century he produced a series of treatises based on what he called "natural principles." These principles are expressions of the age-old laws of proportion. Rameau's explanations of such basic harmonic concepts as the progression of chords, the invertibility of chords, chord-building by thirds and the relation of chords and melody make him the creator of the modern science of harmony. Yet his writings are based on and reconciled with the previous discoveries of such theorists as Zarlino—thinkers who walked the well-worn path leading back to antiquity.

It was also in the early 18th century

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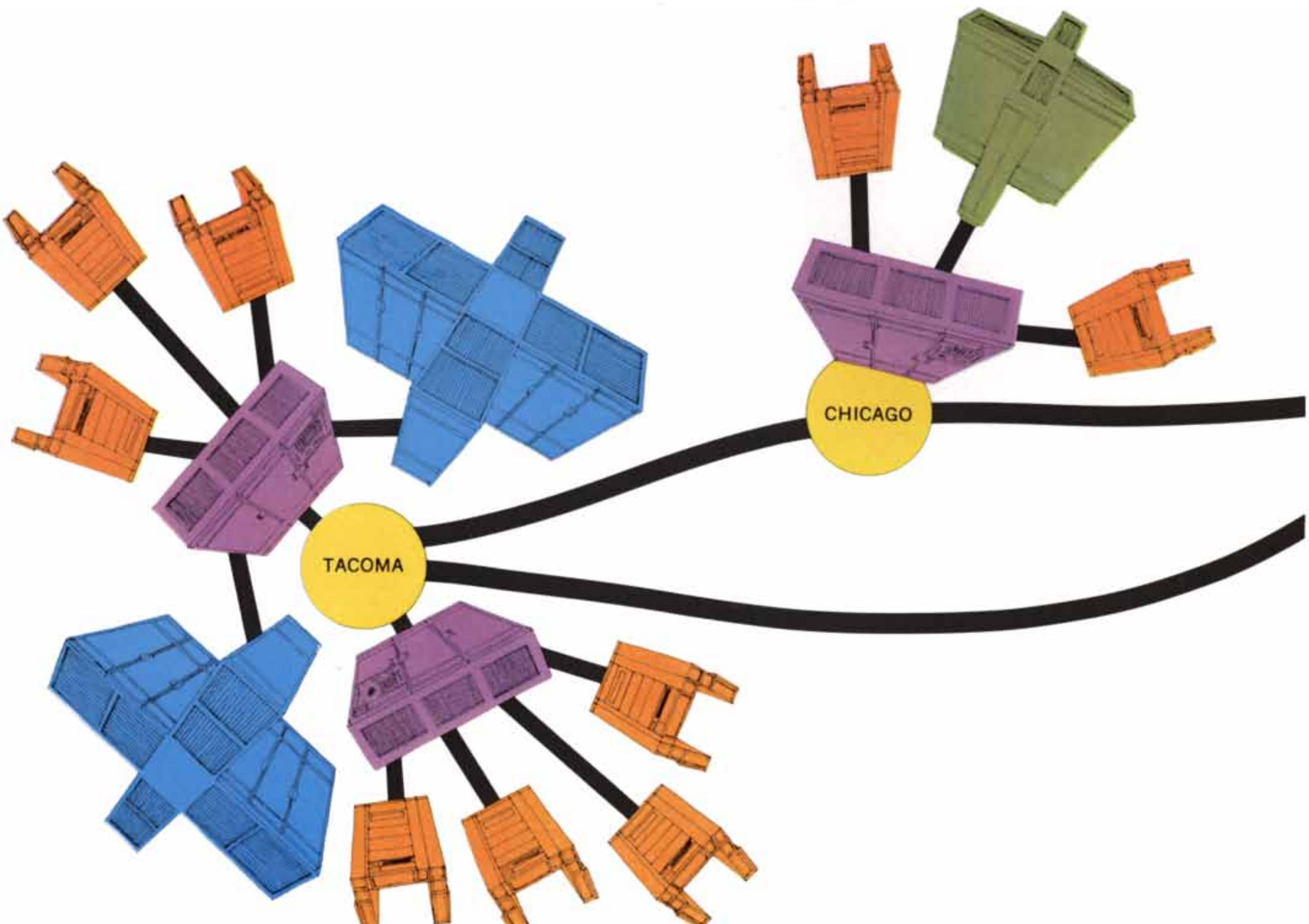

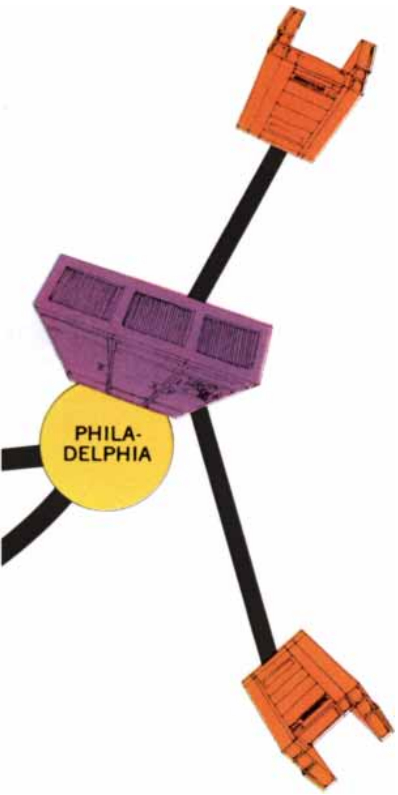

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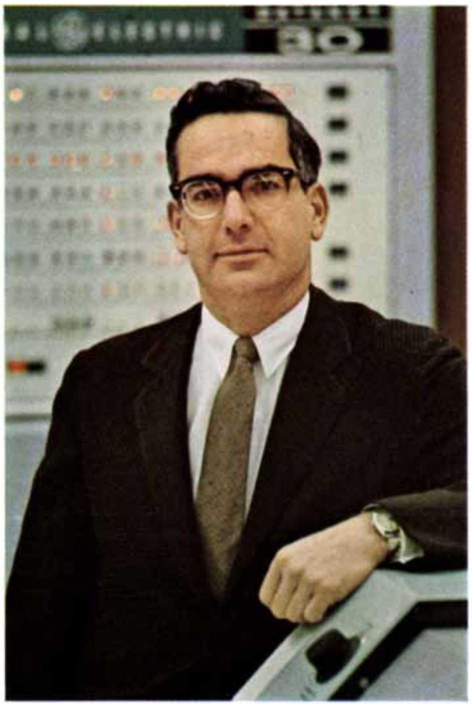

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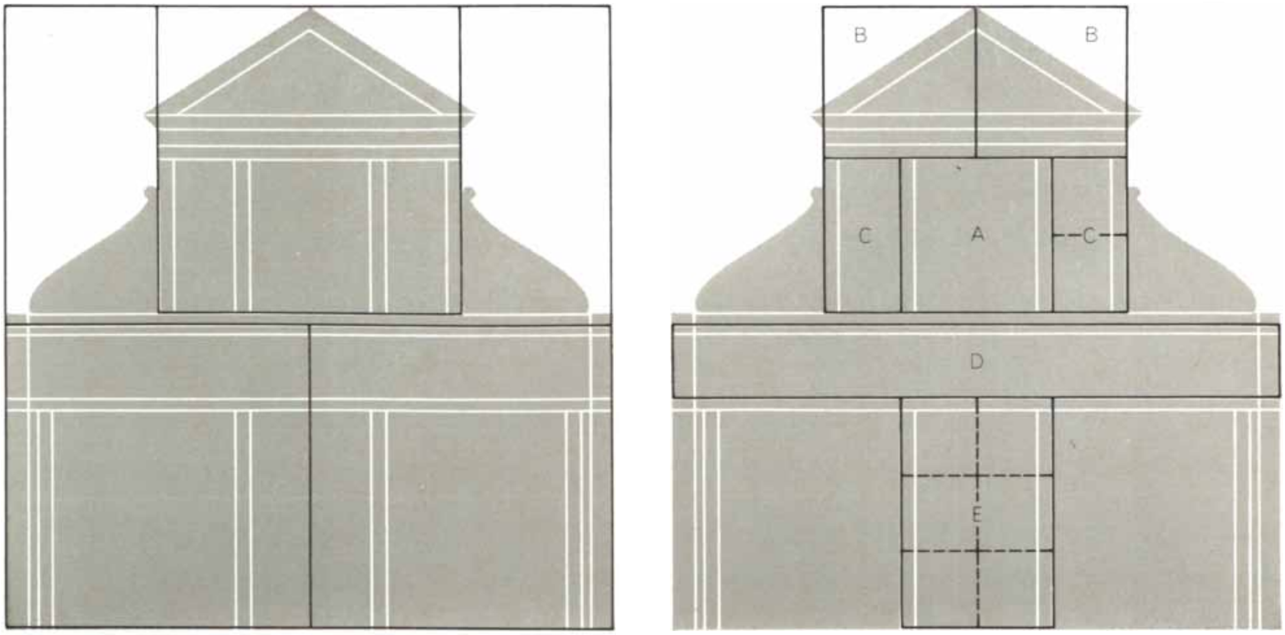


SIMPLE RATIOS were employed by the Italian architect Alberti in designing the façade of Santa Maria Novella in Florence, as shown by Rudolf Wittkower of Columbia University. The black lines indicate how the façade is made up of squares related in the ratio 1 : 2, as in an octave (*left*). The same ratio recurs in the subunits (*right*). The sides of the central bay of the upper story (*A*) form a square half the width of the full story. Squares of the same size enclose the pediment and entablature (*B*); these are twice the width of the side bays (*C*) and twice the height of the attic (*D*). The ratio of the width to the height of the entrance bay (*E*) is 2 : 3.

that the French physicist Joseph Sauveur achieved perhaps the most concrete theoretical reconciliation of old and new with his discovery of overtones: the fact that a vibrating string sounds not only a fundamental note but also a subsidiary series of higher notes that are integral multiples (as defined by speed of vibration) of the fundamental one, with the most important of these notes lying an octave, a fifth and a fourth apart. The phenomenon is also known as the harmonic series and has been called the "chord of nature."

Sauveur's discovery marks a major division in the history of musical thought. Before his time the power of music was largely explained through mathematical flights of reason and fancy. Since his time most theorists have tried to discover the secret of music in acoustical laws, such as the law of overtones. The name of Pythagoras still figures importantly in most books on acoustics, but to regard the modern science of acoustics as a continuation of Pythagoreanism would be to equate two different modes of thought.

Against the historical background that I have sketched let us consider further the role of mathematics from the viewpoint of the composer. The fact is that the string of the Pythagoreans has always vibrated more in minds than in ears, because the composer has seldom been able to put the proportions to direct use during the process of musical composition. At face value they seem too simple; when they are applied subliminally or "in principle," they seem to disappear altogether. To put the matter another way, composers usually realize the mathematical bases of composition only after the composing is done.

Nonetheless, there have been few periods in Western history when most composers did not perceive mathematical order in the structure of music and strenuously try to find a meeting ground between the old mathematical laws and the creation of new music. The attempts have become more subtle, but the question remains: Are there any valid mathematical approaches to composition?

Among the groups of composers who would answer the question affirmatively are the serialists, whose "12-tone system" is based on the harmonic and melodic equivalence of the 12 tones of the harmonic scale (the white and black keys from one *C* to the next on a piano). Serialism was invented some 50 years ago by Arnold Schoenberg, who saw the technique as a unifying device for atonal music, or music without a key. In this technique, which has since been extended, the 12 notes are arranged in some specific order that is then used as the basis for a composition. The series of tones can be represented as a series of numbers.

A recent chamber work indicates how far the serialist technique has moved. It is *Sestina*, by Ernst Křenek. This composition is serially determined not only in pitch but also in rhythm and in density (the number of instruments playing at any given moment). It is not only a model of the uncompromisingly mathematical in music but also a manifesto: one of the lines of its poetry, which was written by Křenek, states "What looks ahead subordinates itself to number."

For the most part, however, mathematics swims seductively just below the surface of music. It is a naiad gazing at the composer, seemingly within reach but actually unreachable. Its presence is explained by the unshakable principle that music, like all other arts, must be founded on some kind of order.

Considering the seductiveness of the naiad, is it any wonder that Athanasius Kircher, the 17th-century German mathematician and self-styled musical encyclopedist, built a composing machine whose numerical combinations would dictate pitch, rhythm and tempo to any composer willing to use it? (Nobody seemed willing.) Is it presumptuous to believe that Mozart, Haydn, Handel and others may not have had their tongues completely in their cheeks when they wrote music dictated by the throw of dice? Can we begin to understand the mathematical preoccupations of such contemporary composers as Křenek, Karlheinz Stockhausen, Milton Babbitt and Pierre Boulez? Should we be more tolerant of music generated by computer?

Non-Cantorian Set Theory

In 1963 it was proved that a celebrated mathematical hypothesis put forward by Georg Cantor could not be proved. This profound development is explained by analogy with non-Euclidean geometry

by Paul J. Cohen and Reuben Hersh

The abstract theory of sets is currently in a state of change that in several ways is analogous to the 19th-century revolution in geometry. As in any revolution, political or scientific, it is difficult for those participating in the revolution or witnessing it to foretell its ultimate consequences, except perhaps that they will be profound. One thing that can be done is to try to use the past as a guide to the future. It is an unreliable guide, to be sure, but better than none.

We propose in this article to use the oft-told tale of non-Euclidean geometry to illuminate the now unfolding story of nonstandard set theory.

A set, of course, is one of the simplest and most primitive ideas in mathematics, so simple that today it is part of the kindergarten curriculum. No doubt for this very reason its role as the most fundamental concept of mathematics was not made explicit until the 1880's. Only then did Georg Cantor make the first nontrivial discovery in the theory of sets.

To describe his discovery we must first explain what we mean by an infinite set. An infinite set is merely a set with an infinite number of distinct elements; for example, the set of all "natural" numbers (1, 2, 3 and so on) is infinite. So too is the set of all the points on a given line segment.

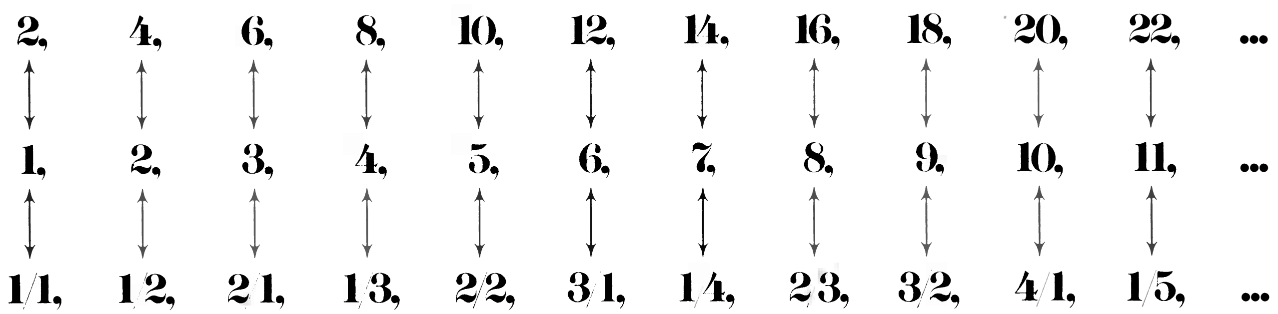
Cantor pointed out that even for infinite sets it makes sense to talk about the number of elements in the set, or at least to state that two different sets have the same number of elements. Just as with finite sets, we can say that two sets have the same number of elements—the same "cardinality"—if we can match up the elements in the two sets one for one. If this can be done, we call the two sets equivalent.

The set of all natural numbers can be matched up with the set of all even numbers, and also with the set of all fractions [*see illustration below*]. These two examples illustrate a paradoxical property of infinite sets: an infinite set can be equivalent to one of its subsets. In fact, it is easily proved that a set is infinite if, and only if, it is equivalent to some proper subset of itself.

All of this is engaging, but it was not new with Cantor. The notion of the cardinality of infinite sets would be interesting only if it could be shown that not all infinite sets have the same cardinality. It was this that was Cantor's first great discovery in set theory. By his famous diagonal proof he showed that the set of natural numbers is *not* equivalent to the set of points on a line segment [*see illustration on opposite page*].

Thus there are at least two different kinds of infinity. The first, the infinity of the natural numbers (and of any equivalent infinite sets), is called aleph nought ($\aleph_0$). Sets with cardinality $\aleph_0$ are called countable. The second kind of infinity is the one represented by a line segment. Its cardinality is designated by a lowercase German *c* ($\mathfrak{c}$), for "continuum." *Any* line segment, of arbitrary length, has cardinality $\mathfrak{c}$ [*see illustration on page 106*]. So does any rectangle in the plane, any cube in space, or for that matter all of unbounded *n*-dimensional space, whether *n* is 1, 2, 3 or 1,000!

Once a single step up the chain of infinities has been taken, the next follows naturally. We encounter the notion of the set of all subsets of a given set [*see illustration on page 111*]. If the



SET IS TERMED COUNTABLE if it can be matched one for one with the natural numbers (*middle row*). Thus the set of all even numbers (*top row*) is countable. The set of all fractions (*bottom row*) is also countable. The fractions shown here are the ones used by the German mathematician Georg Cantor (1845–1918); they are not in their natural order but in order according to the sum of the numerator and the denominator. Both examples show that an infinite set, unlike a finite set, can be equivalent to one of its subsets.

original set is called A, this new set is called the power set of A and is written 2^A. And just as we obtain the power set 2^A from A, we can next obtain $2^{(2^A)}$ from 2^A, and so on as long as we please.

Cantor proved that whether A is finite or infinite, 2^A is never equivalent to A. Therefore the procedure of forming the set of all subsets generates an endless chain of increasing, nonequivalent infinite sets. In particular, if A is the set of natural numbers, then it is easy to prove that 2^A (the set of all sets of natural numbers) is equivalent to the continuum (the set of all points on a line segment). In brief,

$$2^{\aleph_0} = \mathfrak{c}.$$

At this point a question may occur to the reader. Is there an infinite set with cardinality *between* $\aleph_0$ and $\mathfrak{c}$? That is, is there on a line segment an infinite set of points that is not equivalent to the whole segment, and also not equivalent to the set of natural numbers?

This question occurred to Cantor, but he was unable to find any such set. He concluded—or rather conjectured—that no such thing exists. This guess of Cantor's acquired the name "the continuum hypothesis." Its proof or disproof was first on the celebrated list of unsolved mathematical problems drawn up by David Hilbert in 1900. Only in 1963 was it finally settled. It was settled, however, in a sense utterly different from what Hilbert had in mind.

To tackle this problem one could no longer rely on Cantor's definition of a set as "any collection into a whole of definite and separate objects of our intuition or our thought." In fact, this definition, seemingly so transparent, turned out to conceal some treacherous pitfalls. An instance is the sad experience suffered by Gottlob Frege in 1902. Frege was about to publish a monumental work in which arithmetic was reconstructed on the foundation of set theory, that is, on the foundation of "intuitive" set theory as it was then known on the basis of Cantor's work. At this point Frege received a letter from the young Bertrand Russell, which he acknowledged by adding this postscript to his treatise: "A scientist can hardly meet with anything more undesirable than to have the foundation give way just as the work is finished. In this position I was put by a letter from Mr. Bertrand Russell as the work was nearly through the press."

Russell's blow consisted in pointing out a simple conundrum. There are two kinds of sets. First there are those, such as "the set of all objects describable in

1. .18347984639001...
2. .36948570110924...
3. .50472200173996...
4. .99801230109487...
5. .00102305497610...
6. .51546798371238...
7. .55119871350426...

⋮ ⋮

SET OF REAL NUMBERS IS UNCOUNTABLE, as Cantor showed in his famous diagonal proof. Here a sample of the set is listed in decimal form and at random. If one takes the first digit of the first number, the second digit of the second and so on (*color*), one obtains a real number whose infinite decimal expansion is .1640277. . . . If one randomly changed every digit in the expansion, one might get .2751388. . . . A moment's thought will show that the new number is different in at least one place from every number on the list. Hence the number was not present on the list, and it has been proved that the list was incomplete.

exactly 11 English words," having the peculiar property that they themselves satisfy their defining property; in other words, sets that contain themselves as elements. We call them R sets, the R standing for Russell. Then there are all other sets—sets that do not belong to themselves. Call them the non-R sets. Now, said Russell, consider the collection of all non-R sets. (The word "collection" is introduced here simply as a convenient synonym for "set.") Call this set M. Then M is either an R set or a non-R set. But if M is a non-R set, then it belongs to M, by definition of M, so that it is an R set, by definition of R sets. This is a contradiction. On the other hand, if M is an R set, then by definition of M it does not belong to M. It does not belong to itself, that is, it is not an R set, which is again a contradiction.

The moral is this: The free use of Cantor's intuitive notion of a set can lead to contradictions. Set theory can serve as a secure foundation for mathematics only if a more sophisticated approach is employed to steer clear of antinomies, as contradictions of the type proposed by Russell later came to be known.

It has happened before that unwelcome paradoxes have intruded into a seemingly clear mathematical theory. There are the paradoxes of Zeno, which revealed to the Greeks unsuspected complexities in intuitive concepts of lines and points. We can draw an analogy: As Russell found a contradiction in the unrestricted use of the intuitive concept of set, so Zeno had found contradictions in the unrestricted use of the intuitive concepts of "line" and "point."

In its beginning with Thales in the sixth century B.C. Greek geometry had relied on an unspecified intuitive concept of "line" and "point." Some 300 years later, however, Euclid had given these concepts an axiomatic treatment. For Euclid geometric objects were still intuitively known real entities, but insofar as they were the subject of geometrical reasoning they were specified by certain unproved assertions ("axioms" and "postulates"), on the basis of which all their other properties were supposed to be proved as "theorems." We do not know if, and to what extent, this development was a response to paradoxes such as Zeno's. There is no doubt, however, that to the Greeks geometry was made much more secure by virtue of depending (at least so they believed and intended) only on logical inference from a small number of clearly stated assumptions.

The analogous development for set theory took not 300 years but only 35. If

Cantor played the role of Thales—the founder of the subject, who was able to rely on intuitive reasoning alone—then the role of Euclid was played by Ernst Zermelo, who in 1908 founded axiomatic set theory. Of course, Euclid was really only one of a long succession of Greek geometers who created "Euclidean geometry"; so also Zermelo was only the first of half a dozen great names in the creation of axiomatic set theory.

Just as Euclid had listed certain properties of points and lines and had regarded as proved only those theorems in geometry that could be obtained from these axioms (and not from any possibly intuitive arguments), so in axiomatic set theory a set is regarded simply as an undefined object satisfying a given list of axioms. Of course, we still want to study sets (or lines, as the case may be), and so the axioms are chosen not arbitrarily but in accord with our intuitive notion of a set or a line. Intuition is nonetheless barred from any further formal role; only those propositions are accepted that follow from the axioms. The fact that objects described by these axioms actually may exist in the real world is irrelevant to the process of formal deduction (although it is essential to discovery).

We agree to act as if the symbols for "line," "point" and "angle" in geometry, or the symbols for "set," "is a subset of" and so on in set theory, are mere marks on paper, which may be rearranged only according to a given list of rules (axioms and rules of inference). Accepted as theorems are only those statements that are obtained according to such manipulations of symbols. (In actual practice only those statements are accepted that clearly *could* be obtained in this manner if one took enough time and trouble.)

Now, in the history of geometry one postulate played a special role. This was the parallel postulate, which says that through a given point there can be drawn precisely one line parallel to a given line. The difficulty with this statement as an axiom is that it does not have the self-evident character one prefers in the foundation stones of a mathematical theory. In fact, parallel lines are defined as lines that never meet, even if they are extended indefinitely ("to infinity"). Since any lines we draw on paper or on a blackboard have finite length, this is an axiom that by its nature cannot be verified by direct observation of the senses. Nonetheless, it plays an indispensable role in Euclidean geometry. For many centuries a leading problem in geometry was to *prove* the parallel postulate, to show that it could be obtained as a theorem from the more self-evident Euclidean axioms.

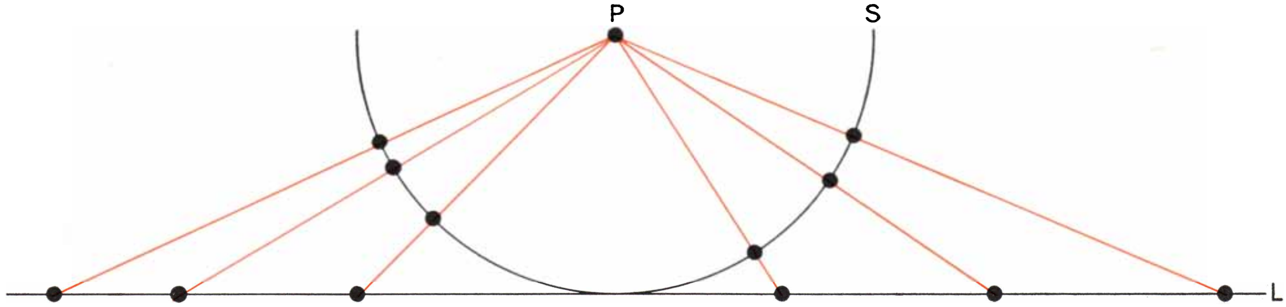
In abstract set theory, it so happens, there also was a particular axiom that some mathematicians found hard to swallow. This was the axiom of choice, which says the following: If α is any collection of sets $\{A, B, \ldots\}$, and none of the sets in α is empty, then there exists a set Z consisting of precisely one element each from A, from B and so on through all the sets in α. For instance, if α consists of two sets, the set of all triangles and the set of all squares, then α clearly satisfies the axiom of choice. We merely choose some particular triangle and some particular square and then let these two elements constitute Z.

Most people find the axiom of choice, like the parallel postulate, intuitively very plausible. The difficulty with it is in the latitude we allow α: "any" collection of sets. As we have seen, there are endless chains of ever bigger infinite sets. For such an inconceivably huge collection of sets there is no way of actually choosing one by one from all its member sets. If we accept the axiom of choice, our acceptance is simply an act of faith that such a choice is possible, just as our acceptance of the parallel postulate is an act of faith about how lines would act if they were extended to infinity. It turns out that from the innocent-seeming axiom of choice some unexpected and extremely powerful conclusions follow. For example, we are able to use inductive reasoning to prove statements about the elements in *any* set, in much the same way that mathematical induction can be used to prove theorems about the natural numbers 1, 2, 3 and so on.

The axiom of choice played a special role in set theory. Many mathematicians thought its use should be avoided whenever possible. Such a form of axiomatic set theory, in which the axiom of choice is *not* assumed to be either true or false, would be one on which almost all mathematicians would be prepared to rely. In what follows we use the term "restricted set theory" for such an axiom system. We use the term "standard set theory" for the theory based on the full set of axioms put forward by Zermelo and Abraham Fraenkel: restricted set theory *plus* the axiom of choice.

In 1938 this subject was profoundly illuminated by Kurt Gödel. Gödel is best known for his great "incompleteness" theorems of 1930–1931 [see "Gödel's Proof," by Ernest Nagel and James R. Newman; SCIENTIFIC AMERICAN, June, 1956]. Here we refer to later work by Gödel that is not well known to nonmathematicians. In 1938 Gödel proved the following fundamental result: If restricted set theory is consistent, then so is standard set theory. In other words, the axiom of choice is no more dangerous than the other axioms; if a contradiction can be found in standard set theory, then there must already be a contradiction hidden within restricted set theory.

But that was not all Gödel proved. We remind the reader of Cantor's "continuum hypothesis," namely that no in-



INFINITE LINE AND FINITE LINE SEGMENT can also be shown to have a one-to-one correspondence. Here P is the center of a semicircle S that is tangent to an infinite line L. A ray from P cuts S at only one point. In this way rays from P give a one-to-one match between points on S and points on L. As the ray changes direction from left to right no point is omitted from either S or L. Thus a one-to-one correspondence exists between the points on an infinite line and the points on a finite segment of arbitrary length.

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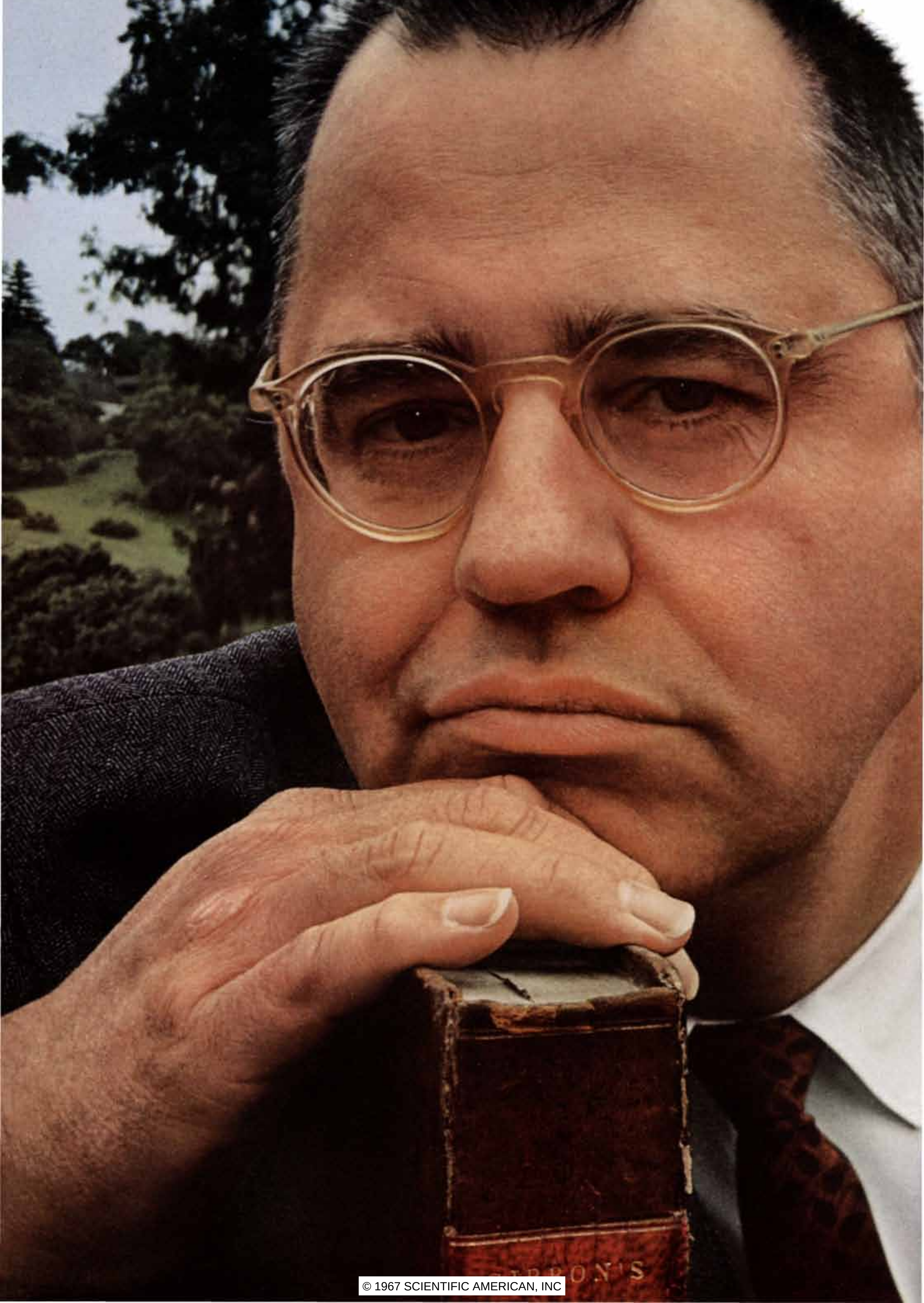

This philosopher wants tomorrow's students to get the best teaching possible–with or without computers.

What's he doing at IBM?

Says Bruse Moncreiff, a philosopher by training: "You'll find computers on many campuses today, doing many things. And one current experiment which may prove increasingly important is computer-assisted instruction (CAI). But we must learn from the teachers—let them decide if computers can be useful as a teaching aid."

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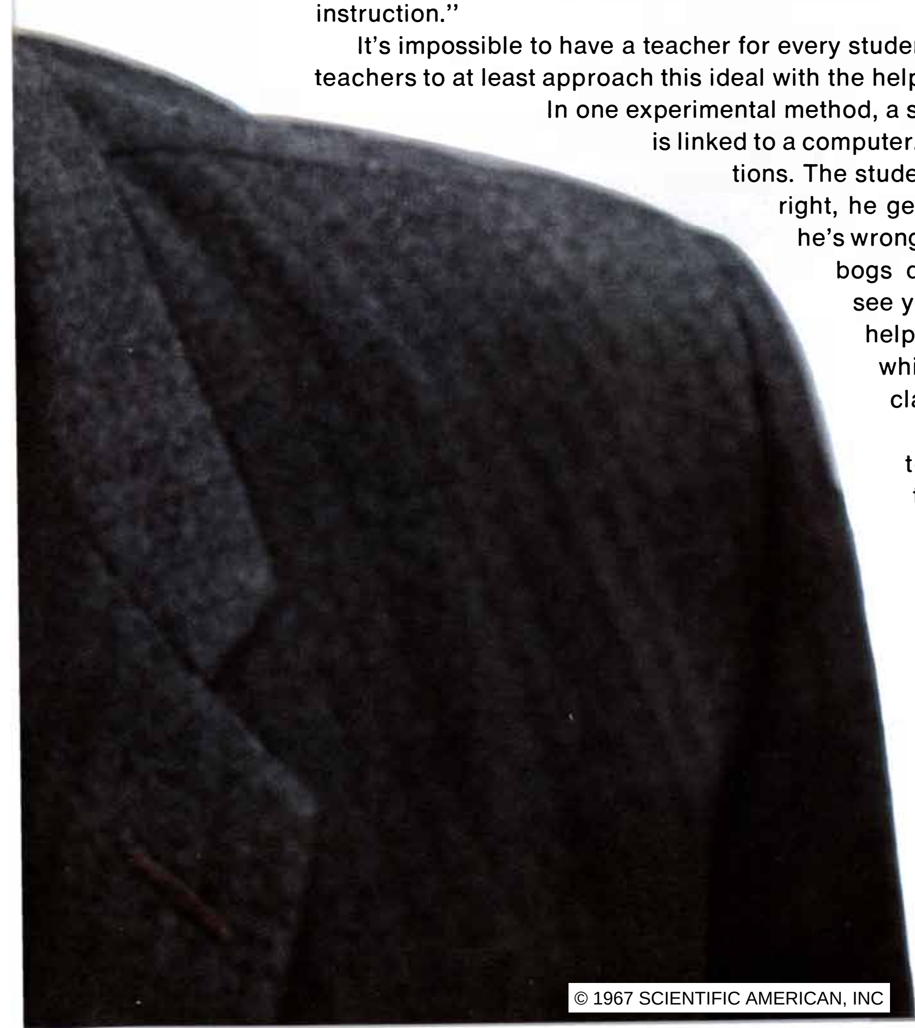
"Today, both children and adults must be better educated, to survive in a world where change has become the norm," says Moncreiff. "And because each person is different from the next, one ideal method of teaching is one-to-one—individual instruction."

It's impossible to have a teacher for every student. But it might be possible for teachers to at least approach this ideal with the help of computers.



In one experimental method, a student sits at a typewriter that is linked to a computer. The computer types out questions. The student types back answers. If he's right, he gets a more difficult question. If he's wrong, he gets a hint; and if he really bogs down, the suggestion, "better see your teacher." The teacher can help the student where he needs it, while the other members of the class continue uninterrupted.

"The computer's role as a teaching aid demands hard thought," says Moncreiff. "Promising as it may seem to us, we must take our lead from those who know the most—the teachers themselves. It is they who will have the final say."

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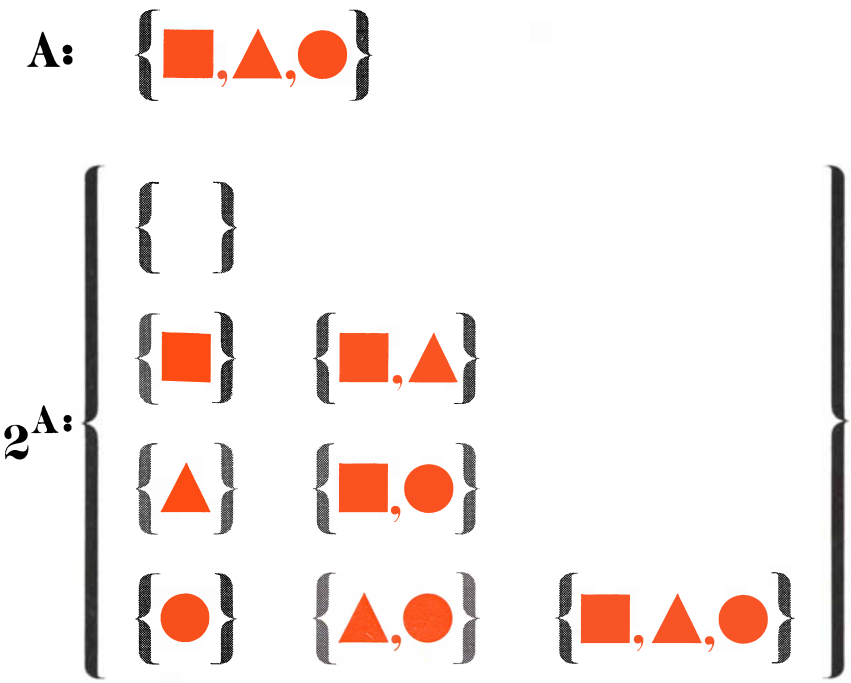


SET OF ALL SUBSETS OF A GIVEN SET is illustrated. The square, triangle and circle at top form the three-element set A. This set has 2^3, or 8, subsets (provided that the whole set and the empty set are somewhat improperly included). This new set consisting of eight elements is called the power set of A, and it is denoted 2^A. If A has n elements, the power set of A has 2^n elements. If A is infinite, 2^A is also infinite, and it is not equivalent to A.

finite cardinal exists that is greater than $\aleph_0$ and smaller than $\mathfrak{c}$. Gödel also showed that we can safely take the continuum hypothesis as an additional axiom in set theory; that is, if the continuum hypothesis plus restricted set theory implies a contradiction, then again there must already be a contradiction hidden within restricted set theory. This was a half-solution of Cantor's problem; it was not a *proof* of the continuum hypothesis but only a proof that it cannot be disproved.

To understand how Gödel achieved his results we need to understand what is meant by a model for an axiom system. Let us return for a moment to the axioms of plane geometry. If we take these axioms, including the parallel postulate, we have the axioms of Euclidean geometry; if instead we keep all the other axioms as before but replace the parallel postulate by its negation, we have the axioms of a non-Euclidean geometry. For both axiom systems—Euclidean and non-Euclidean—we ask: Can these axioms lead to a contradiction?

To ask the question of the Euclidean system may seem unreasonable. How could there be anything wrong with our familiar, 2,000-year-old high school geometry? On the other hand, to the nonmathematician there certainly is something suspicious about the second axiom system, with its denial of the intuitively plausible parallel postulate. Nonetheless, from the viewpoint of 20th-century mathematics the two kinds of geometry stand more or less on an equal footing. Both are sometimes applicable to the physical world and both are consistent, in a relative sense we shall now explain.

First we show that non-Euclidean geometry is consistent. In order to do this we merely replace the word "line" everywhere by the phrase "great circle," a line formed on the surface of a sphere by a plane passing through the center of the sphere. We now regard the axioms as statements about points and great circles on a given sphere. Moreover, we agree to identify each pair of diametrically opposite points on the sphere as a single point. If the reader prefers, he can imagine the axioms of non-Euclidean geometry rewritten, with the word "line" everywhere replaced by "great circle," the word "point" everywhere replaced by "point pair." Then it is evident that all the axioms are true, at least insofar as our ordinary notions about the surface of a sphere are true. In fact, from the axioms of Euclidean solid geometry one can easily prove as theorems that the surface of a sphere is a non-Euclidean surface in the sense we have just described. In other words, we now see that if the axioms of non-Euclidean geometry led to a contradiction, then so would the ordinary Euclidean geometry of spheres lead to a contradiction. Thus we have a *relative* proof of consistency; if Euclidean three-dimensional geometry is consistent, then so is non-Euclidean two-dimensional geometry. We say that the surface of the Euclidean sphere is a model for the axioms of non-Euclidean geometry. (In the particular model we have used the parallel postulate fails because there are no parallel lines. It is also possible to construct a surface, the "pseudosphere," for which the parallel postulate is false because there is more than one line through a point parallel to a given line.)

The invention of non-Euclidean geometry, and the recognition that its consistency is implied by the consistency of Euclidean geometry, was the work of many great 19th-century mathematicians; we mention the name of Bernhard Riemann in particular. Only in the 20th century was the question raised of whether or not Euclidean geometry itself is consistent.

This question was asked and answered by David Hilbert. Hilbert's solution was a simple application of the idea of a coordinate system. As many college freshmen learn, to each point in the plane we can associate a pair of numbers: its x and y coordinates. Then with each line or circle we can associate an equation: a relation between the x and y coordinates that is true only for the points on that line or circle. In this way we set up a correspondence between geometry and elementary algebra. For every statement in one subject there is a corresponding statement in the other. It follows that the axioms of Euclidean geometry can lead to a contradiction only if the rules of elementary algebra—the properties of the ordinary real numbers—can lead to a contradiction. Here again we have a relative proof of consistency. Non-Euclidean geometry was consistent if Euclidean geometry was consistent; now Euclidean geometry is consistent if elementary algebra is consistent. The Euclidean sphere was a model for the non-Euclidean plane; the set of pairs of coordinates is in turn a model for the Euclidean plane.

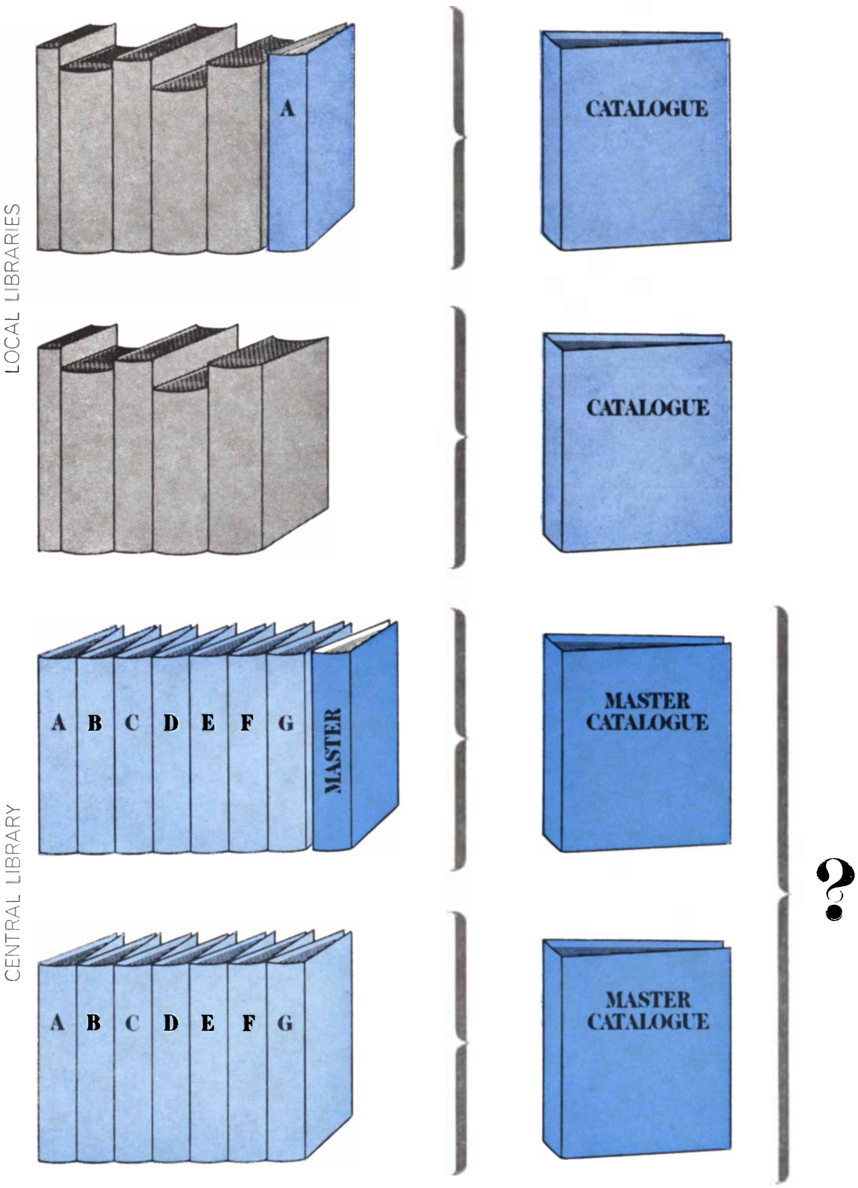
With these examples before us we can say that Gödel's proof of the relative consistency of the axiom of choice and of the continuum hypothesis is analogous to Hilbert's proof of the relative consistency of Euclidean geometry. In both instances the standard theory was justified in terms of a more elementary one. Of course, no one ever seriously doubted the reliability of Euclidean geometry, whereas such outstanding mathematicians as L. E. J. Brouwer, Hermann Weyl and Henri Poincaré had grave doubts about the axiom of choice. In this sense Gödel's result had a much greater impact and significance.

The analogous development with respect to non-Euclidean geometry—what we might call non-Cantorian set theory—has taken place only since 1963, in the work of one of the authors of this article (Cohen). What is meant by "non-Cantorian set theory"? Just as Euclidean and non-Euclidean geometry use the same axioms, with the one exception of the parallel postulate, so standard ("Cantorian") and nonstandard ("non-Cantorian") set theory differ only in one axiom. Non-Cantorian set theory takes the axioms of restricted set theory and adds not the axiom of choice but rather one or another form of the negation of the axiom of choice. In particular we can take as an axiom the negation of the continuum hypothesis. Thus, as we shall explain, there now exists a complete solution of the continuum problem. To Gödel's discovery that the continuum hypothesis is not disprovable is added the fact that it is also not provable.

Both Gödel's result and the new discoveries require the construction of a model, just as the consistency proofs for geometry that we have described required a model. In both cases we want to prove that if restricted set theory is consistent, then so is standard set theory (or nonstandard theory).

Gödel's idea was to construct a model for restricted set theory, and to prove that in this model the axiom of choice and the continuum hypothesis were theorems. He proceeded in the following way. Using only the axioms of restricted set theory [*see illustration on page 114*], we are guaranteed first the existence of at least one set (the empty set) by Axiom 2; then by Axiom 3 and Axiom 4 we are guaranteed the existence of an infinite sequence of ever larger finite sets; then by Axiom 5, the existence of an infinite set; then by Axiom 7, of an endless sequence of ever larger (nonequivalent) infinite sets, and so on. In essentially this way Gödel specified a class of sets by the manner in which they could actually be constructed in successive steps from simpler sets. These sets he called the "constructible sets"; their existence was guaranteed by the axioms of restricted set theory. Then he showed that within the realm of the constructible sets the axiom of choice and the continuum hypothesis can both be proved. That is to say, first, from any constructible collection α of constructible sets (A, B, . . .) one can choose a constructible set Z consisting of at least one element each from A, B and so on. This is the axiom of choice, which here might more properly be called the theorem of choice. Second, if A is any infinite constructible set, then there is no constructible set "between" A and 2^A (bigger than A, smaller than the power set of A and equivalent to neither). If A is taken as the first infinite cardinal, this last statement is the continuum hypothesis.

Hence a "generalized continuum hypothesis" was proved in the case of *constructible* set theory. Gödel's work would therefore dispose of these two questions completely if we were prepared to adopt the axiom that only constructible sets exist. Why not do so? Because one feels it is unreasonable to insist that a set must be constructed according to *any* prescribed formula in order to be recognized as a genuine set. Thus in ordinary (not necessarily constructible) set theory neither the axiom of choice nor the continuum hypothesis had been proved. At least this much was



RUSSELL'S PARADOX is illustrated by supposing that in a certain country it is the custom of librarians to list their books not in a card catalogue but in a looseleaf catalogue; that is, the catalogue itself is a book. Some librarians list the catalogue itself in the catalogue (*top*); some do not (*second from top*). The first kind of catalogue is called an *R*-set, after Bertrand Russell; *R*-sets are sets that include themselves. What happens, however, if the head librarian of the country decides to make a master catalogue of all the catalogues that do not list themselves? Does his own catalogue belong in the master catalogue or not?

"COMMON NOTIONS"

1. Things that are equal to the same thing are also equal to one another.
2. If equals are added to equals, the wholes are equal.
3. If equals are subtracted from equals, the remainders are equal.
4. Things that coincide with one another are equal to one another.
5. The whole is greater than the part.

"POSTULATES"

1. (It is possible) to draw (exactly one) straight line from any point to any point.
2. (It is possible) to extend a finite straight line continuously in a straight line.
3. (It is possible) to describe a circle with any center and distance.
4. All right angles are equal to one another.
5. If a straight line falling on two straight lines makes the interior angles on the same side less than two right angles, the two straight lines, if produced indefinitely, meet on that side on which are the angles less than the two right angles.

EUCLID'S AXIOMS were of two kinds: "common notions" and "postulates." The Scottish physicist and mathematician John Playfair (1748–1819) is identified with an axiom that may be shown to be equivalent to Euclid's Postulate 5: Through a given point *A* not on a given line *m* there passes one line that does not intersect *m*. A non-Euclidean geometry is obtained by replacing "one" with either "none" or "more than one." It should be said that Euclid's axioms are not clear or complete by modern standards.

certain: either of them could be assumed without causing any contradiction unless the "safe" axioms of restricted set theory already are self-contradictory. Any contradiction they cause must already be present in constructible set theory, which is a model for ordinary set theory. In other words, it was known that neither could be disproved from the other axioms but not whether they could be proved.

Here the analogy with the parallel postulate in Euclidean geometry becomes particularly apt. That Euclid's axioms are consistent was taken for granted until quite recently. The ques-

$\forall$	FOR ALL	$\leftrightarrow$	IF AND ONLY IF	$\in$	IS A MEMBER (ELEMENT) OF
$\exists$	THERE EXISTS	$\vee$	OR	$=$	EQUALS
$\exists!$	THERE EXISTS UNIQUELY	&	AND	$\neq$	DOES NOT EQUAL
$\cup$	UNION	$\sim$	NOT	ϕ	THE EMPTY SET
$\rightarrow$	IMPLIES	$\subseteq$	IS A SUBSET OF		

1. AXIOM OF EXTENSIONALITY

$\forall x, y\ (\forall z\ (z \in x \leftrightarrow z \in y) \rightarrow x = y).$

Two sets are equal if and only if they have the same members.

2. AXIOM OF THE NULL SET

$\exists x\ \forall y\ (\sim y \in x).$

There exists a set with no members (the empty set).

3. AXIOM OF UNORDERED PAIRS

$\forall x, y\ \exists z\ \forall w\ (w \in z \leftrightarrow w = x \vee w = y).$

If x and y are sets, then the (unordered) pair $\{x,y\}$ is a set.

4. AXIOM OF THE SUM SET OR UNION

$\forall x\ \exists y \forall z\ (z \in y \leftrightarrow \exists t\ (z \in t\ \&\ t \in x)\ )$

If x is a set of sets, the union of all its members is a set. (For example, if $x = \left\{ \begin{matrix} \{a,b,c\} \\ \{a,c,d,e\} \end{matrix} \right\}$, then the union of the (two) elements of x is the set $\{a,b,c,d,e\}$.)

5. AXIOM OF INFINITY

$\exists x\ (\phi \in x\ \&\ \forall y\ (y \in x \rightarrow y \cup \{y\} \in x).$

There exists a set x that contains the empty set, and that is such that if y belongs to x, then the union of y and $\{y\}$ is also in x. The distinction between the element y and the singleton set $\{y\}$ is basic. This axiom guarantees the existence of infinite sets.

6_n. AXIOM OF REPLACEMENT

$\forall t_1, \ldots, t_k\ (\forall x\ \exists!\ y\ A_n(x,y;t_1, \ldots, t_k) \rightarrow \forall u\ \exists v\ B(u,v)\ )$ where $B(u,v) \equiv \forall r\ (r \in v \leftrightarrow \exists s\ (s \in u\ \&\ A_n(s,r;t_1, \ldots, t_k)\ )\ ).$

This axiom is difficult to restate in English. It is called 6_n rather than 6 because it is really a whole family of axioms. We suppose that all the formulas expressible in our system have been enumerated; the nth is called A_n. Then the axiom of replacement says that if for fixed $t_1, \ldots, t_k$, $A_n(x,y;t_i)$ defines y uniquely as a function of x, say $y = \varphi(x)$, then for each u the range of φ on u is a set. This means, roughly, that any ("reasonable") property that can be stated in the formal language of the theory can be used to define a set (the set of things having the stated property).

7. AXIOM OF THE POWER SET

$\forall x\ \exists y\ \forall z\ (z \in y \leftrightarrow z \subseteq x).$

This axiom says that there exists for each x the set y of all subsets of x. Although y is thus defined by a property, it is not covered by the replacement axiom because it is not given as the range of any function. Indeed, the cardinality of y will be greater than that of x, so that this axiom allows us to construct higher cardinals.

8. AXIOM OF CHOICE

If $\alpha \rightarrow A_\alpha \neq \phi$ is a function defined for all $\alpha \in x$, then there exists another function $f(\alpha)$ for $\alpha \in x$, and $f(\alpha) \in A_\alpha$.

This is the well-known axiom of choice, which allows us to do an infinite amount of "choosing" even though we have no property that would define the choice function and thus enable us to use 6_n instead.

9. AXIOM OF REGULARITY

$\forall x\ \exists y\ (x = \phi \vee (y \in x\ \&\ \forall z\ (z \in x \rightarrow \sim z \in y)\ )\ ).$

This axiom explicitly prohibits $x \in x$, for example.

ZERMELO-FRAENKEL AXIOMS FOR SET THEORY are listed. In order to state these theorems it is necessary to use the symbols of set theory, a glossary of which is given at top. This axiom system was put forward by Ernst Zermelo and Abraham Fraenkel.

tion that interested geometers was whether or not they are independent, that is, whether the parallel postulate could be proved on the basis of the others. A whole series of geometers tried to prove the parallel postulate by showing that its negation led to absurdities. It seems that Carl Friedrich Gauss was the first to see that these "absurdities" were simply the theorems of a new, non-Euclidean geometry. But what Gauss had the courage to think he did not have the courage to publish. It was left for János Bolyai, Nikolai Ivanovich Lobachevsky and Riemann to carry out the logical consequences of denying the parallel postulate. These consequences were the discovery of "fantastic" geometries that had as much logical consistency as the Euclidean geometry of "the real world." Only after this had happened was it recognized that two-dimensional non-Euclidean geometry was just the ordinary Euclidean geometry of certain curved surfaces (spheres and pseudospheres).

The analogous step in set theory would be to deny the axiom of choice or the continuum hypothesis. By this we mean, of course, that the step would be to prove that such a negation is consistent with restricted set theory, in the same sense in which Gödel had proved that the affirmation was consistent. It is this proof that has been accomplished in the past few years, giving rise to a surge of activity in mathematical logic whose final outcome cannot be guessed.

Since it is a question of proving the relative consistency of an axiom system, we naturally think of constructing a model. As we have seen, the relative consistency of non-Euclidean geometry was established when surfaces in Euclidean three-space were shown to be models of two-dimensional non-Euclidean geometry. In a comparable way, in order to prove the legitimacy of a non-Cantorian set theory in which the axiom of choice or the continuum hypothesis is false we must use the axioms of restricted set theory to construct a model in which the negation of the axiom of choice or the negation of the continuum hypothesis can be proved as theorems.

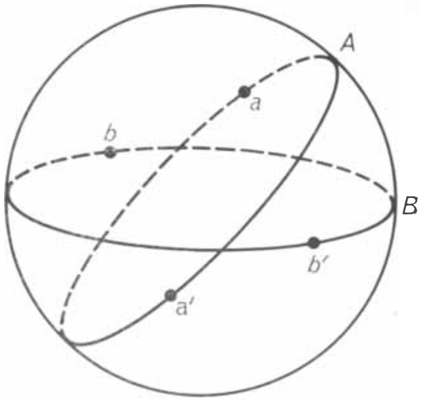
It must be confessed that construction of this model is a complex and delicate affair. This is perhaps to be expected. In Gödel's constructible sets, his model of Cantorian set theory, the task was to create something essentially the same as our intuitive notion of sets but more tractable. In our present task we have to create a model of something unintuitive and strange, using the familiar building stones of restricted set theory.

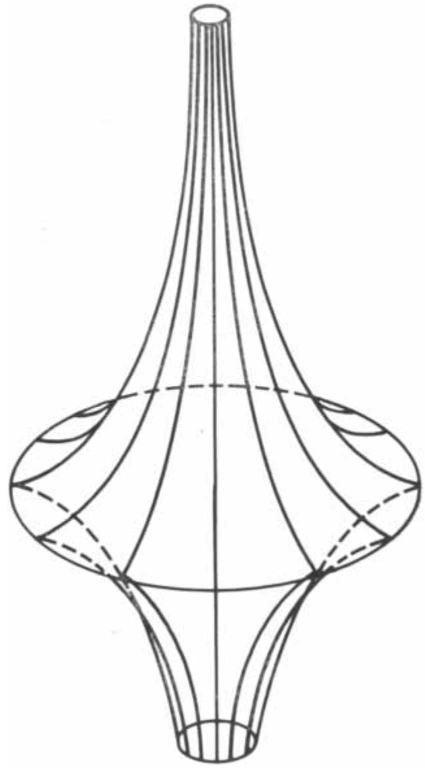
Rather than throw up our hands and say it is impossible to describe this model in a nontechnical article, we shall attempt at least to give a descriptive account of one or two of the leading ideas that are involved. Our starting point is ordinary set theory (without the axiom of choice). We hope only to prove the consistency of non-Cantorian set theory in a relative sense. Just as the models of non-Euclidean geometry prove that non-Euclidean geometry is consistent if Euclidean geometry is consistent, so we shall prove that if restricted set theory is consistent, it remains so if we add the statement "The axiom of choice is false" or the statement "The continuum hypothesis is false." We may now assume that we have available as a starting point a model for restricted set theory. Call this model M; it can be regarded as Gödel's class of constructible sets.

We know from Gödel's work that in order for the axiom of choice or the continuum hypothesis to fail we must add to M at least one nonconstructible set. How to do this? We introduce the letter a to stand for an object to be added to M; it remains to determine what kind of thing a should be. Once we add a we must also add everything that can be formed from a by the permitted operations of restricted set theory: uniting two or more sets to form a new set, forming the power set and so on. The new collection of sets generated in this way by $M + a$ will be called N. The problem is how to choose a in such a way that (1) N is a model for restricted set theory, as M was by assumption, and (2) a is not constructible in N. Only if this is possible is there any hope of denying the axiom of choice or the continuum hypothesis.

We can get a vague feeling of what has to be done by asking how a geometer of 1850 who was trying to discover the pseudosphere might have proceeded. In a very rough sense, it is as if he had started with a curve M in the Euclidean plane, thought of a point a not in that plane, and then connected that point a to all the points in M. Since a is chosen not to lie in the plane of M, the resulting surface N will surely not be the same as the Euclidean plane. Thus it is reasonable to think that with enough ingenuity and technical skill one could show that it is really a model for a non-Euclidean geometry.

The analogous thing in non-Cantorian set theory is to choose the new set a as a nonconstructible set, then to generate a new model N consisting of all sets obtained by the operations of restricted set theory applied to a and to the sets in M. If this can be done, it will have been





ON SURFACE OF A SPHERE "straight line" is interpreted to mean "great circle" (*A and B at top*). Through any pair of diametrically opposite points (*aa′ and bb′*) there pass many great circles. If we interpret "point" to mean "point pair," then Euclid's first postulate is true. The second postulate is true if one allows the extended "straight line" to have a finite total length, or to retrace itself many times as it goes around the sphere. The third postulate is also true if one understands distance to be measured along great circles that can be retraced several times; here a "circle" means merely the set of points on the sphere at a given great-circle distance from a given point. The fourth postulate is likewise true. Playfair's postulate is false, because any two great circles intersect. Thus the sphere is a model of non-Euclidean geometry. So is the pseudosphere (*bottom*), if straight lines are interpreted as being the shortest curves connecting any two points on the surface. On the surface of the pseudosphere there are many "straight lines" that pass through a given point and do not cross a given straight line.

GEOMETRY	STAGE OF DEVELOPMENT	SET THEORY
THALES, PYTHAGORAS	INTUITIVE BASIS FOR FIRST THEOREMS	CANTOR
ZENO	PARADOX REVEALED	RUSSELL
EUDOXUS, EUCLID	AXIOMATIC BASIS FOR STANDARD THEORY	ZERMELO, FRAENKEL, ETC.
DESCARTES, HILBERT	STANDARD THEORY SHOWN (RELATIVELY) CONSISTENT	GODEL
GAUSS, RIEMANN	DISCOVERY OF NONSTANDARD THEORIES	CURRENT WORK
MINKOWSKI, EINSTEIN	APPLICATION OF NONSTANDARD THEORY	? ?

ANALOGY IN DEVELOPMENT of geometry (*left*) and set theory (*right*) is traced historically. Nonstandard (non-Euclidean) geometry has been applied in such theories as Einstein's theory of relativity. Nonstandard set theory has yet to be applied in physics.

proved that one is safely able to negate the axiom of constructibility. Since Gödel showed that constructibility implies the axiom of choice and the continuum hypothesis, this is the necessary first step in negating either of these two statements.

In order to carry out this first step two things must be shown: that *a* can be chosen so that it remains nonconstructible, not only in *M* but also in *N*, and that *N*, like *M*, is a model for restricted set theory. To specify *a* we take a roundabout procedure. We imagine that we are going to make a list of all possible statements about *a*, as a set in *N*. Then *a* will be specified if we give a rule by which we can determine whether or not any such statement is true.

The crucial idea turns out to be to choose *a* to be a "generic" element, that is, to choose *a* so that only those statements are true for *a* that are true for almost all sets in *M*. This is a paradoxical notion. Every set in *M* has both particular special properties that identify it, and also general typical properties that it shares with almost all the other sets in *M*. It turns out to be possible in a precise way to make this distinction between special and generic properties perfectly explicit and formal. Then when we choose *a* to be a generic set (one with, so to speak, no special properties that distinguish it from any set in *M*), it follows that *N* is still a model for restricted set theory. The new element *a* we have introduced has no troublesome properties that can spoil the *M* we started with. At the same time *a* is nonconstructible. Any constructible set has a special character—the steps by which it can be constructed—and our *a* precisely lacks any such individuality.

To construct a model in which the continuum hypothesis is false we must add to *M* not just one new element *a* but a great many new elements. In fact, we must add an infinite number of them. We can actually do this in such a way that the elements we add have cardinality

$$\aleph_2 = 2^{(2^{\aleph_0})}$$

from the viewpoint of the model *M*. Again a rough geometric analogy may be helpful: To a two-dimensional creature living embedded in a non-Euclidean surface it would be impossible to recognize that his world is part of a three-dimensional Euclidean space. In the present instance we, standing outside *M*, can see that we have thrown in only a countable infinity of new elements. They are such, however, that the counting cannot be done by any apparatus available in *M* itself. Thus we obtain a new model *N′*, in which the continuum hypothesis is false. The new elements, which in *N′* play the role of real numbers (that is, points on a line segment), have cardinality greater than $2^{\aleph_0}$, and so there is now an infinite cardinal—namely $2^{\aleph_0}$—that is greater than $\aleph_0$ and yet smaller than $\mathfrak{c}$, since in our model *N′*, $\mathfrak{c}$ is equal to

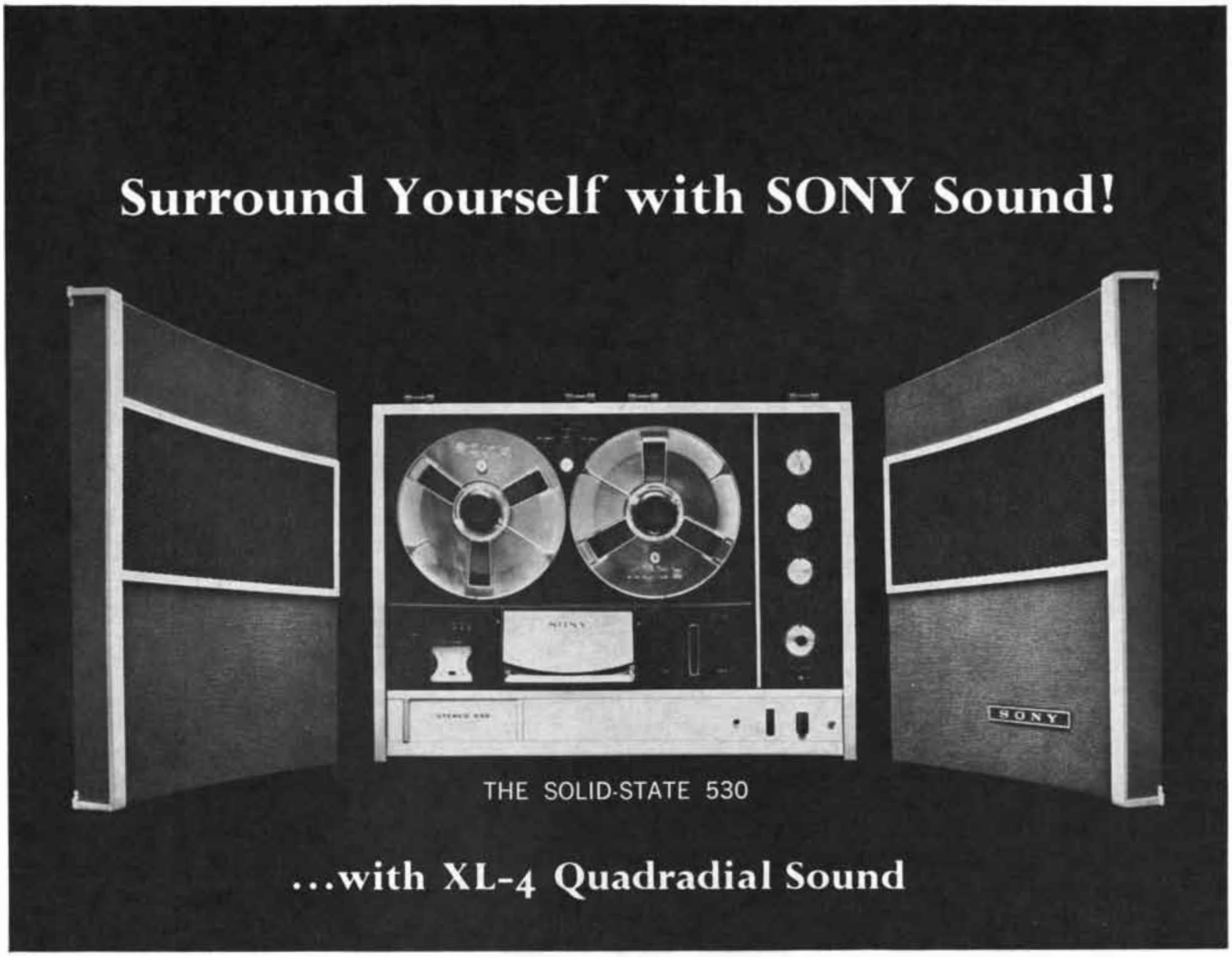
$$2^{(2^{\aleph_0})}.$$

Since we can construct a model of set theory in which the continuum hypothesis is false, it follows that we can add to our ordinary restricted set theory the assumption of the falsity of the continuum hypothesis; no contradiction can result that was not already present. In the same spirit we can construct models for set theory in which the axiom of choice fails. We can even be quite specific about which infinite sets it is possible to "choose from" and which are "too big to choose from."

Whereas Gödel produced his results with a single model (the constructible sets), we have in non-Cantorian set theory not one but many models, each constructed with a particular purpose in mind. Perhaps more important than any of the models is the technique that enables one to construct them all: the notion of "generic" and the related notion of "forcing." Very roughly speaking, generic sets have only those properties they are "forced" to have in order to be setlike. In order to decide whether *a* is "forced" to have a certain property we must look at all of *N*. Yet *N* is not really defined until we have specified *a*! The recognition of how to make this seemingly circular argument noncircular is another key element in the new theory.

What does the history of geometry suggest for the future of set theory? The most remarkable thing about non-Euclidean geometry is that it turned out to be an essential prerequisite for Einstein's general theory of relativity. Riemann created Riemannian geometry for the purely abstract purpose of unifying, clarifying and deepening the non-Euclidean geometry of Lobachevsky, Bolyai and Gauss. This geometry turned out to be the indispensable tool for Einstein's revolutionary reinterpretation of the gravitational force.

Does this example justify an expectation that non-Cantorian set theory someday will find a currently unforeseeable application in the "real" (that is, nonmathematical) world? No one today would venture an answer. Certainly we can see (with hindsight) that geometry has always furnished the essential background in which physical events take place. In that sense it should perhaps have been expected that fundamental advances in geometry would find a physical application. Set theory does not seem today to have any such organic interrelationship with physics. Still, there have been some mathematicians (Stanislaw Ulam, for example) who have proposed that abstract set theory might furnish useful models for theoretical physics. At this stage the safest thing is to refuse to predict anything about the future—except that it is unpredictable.



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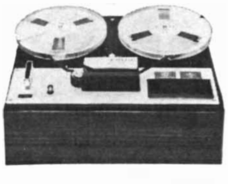

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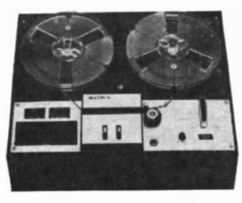

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THE WATER BUFFALO

This gentle beast is a source of power and food for a substantial fraction of humanity. It has much to recommend it for these uses, yet it has been studied far less than many other domestic animals

by W. Ross Cockrill

The water buffalo has long been a major servant of man in the East. The plow it pulls across the padi, or rice, fields today differs in no detail from the one it pulled three centuries ago. The animal plods through its task slowly, but it is sure of foot and easy to manage. Moreover, it is versatile: it not only provides draft power for tilling the padi fields and for many other purposes but also supplies a rich milk and a meat that compares favorably with beef.

A large proportion of the world's water buffaloes live in the countries of South Asia, including some where there is a chronic shortage of food. The water buffalo's contribution to the food supply is a considerable one, and we in the Food and Agriculture Organization of the United Nations (with the support of the Commonwealth of Australia) are studying the animal in order to learn how that contribution might be enhanced. Little is known about the water buffalo's physiology and full potential as a domestic animal; even the elephant, the yak, the camel and the llama are better understood. Still, the water buffalo is an exceptionally productive animal; it is capable of performing work and producing milk on a diet consisting only of stubble. In this regard it surpasses all other animals.

The water buffalo of Asia (*Bubalus bubalis*) is at times confused with its distant cousin the wild buffalo of Africa (*Syncerus caffer*) and even with the American bison (*Bison bison*), but it is not closely related to these animals. It differs from the cattle of the East in a number of particulars; for example, it has no dewlap or hump. It is also distinguished by its proclivity for wallowing in mud or water. Left to itself, it is of nocturnal inclination.

The various breeds of the water buffalo are customarily separated into two groups: river buffaloes, which are found mostly in India, and variants of the swamp buffalo, which are most plentiful in the great rice-growing lands east and south of Burma. Among the river buffalo breeds are the Murrah, Surati and Jaffarabadi. The desi, which means "local," is the most common type. It is a hardy, nondescript mongrel, the result of many generations of haphazard crossbreeding. River buffaloes prefer clean running water to mud, and they are better suited to milk production than the swamp buffalo.

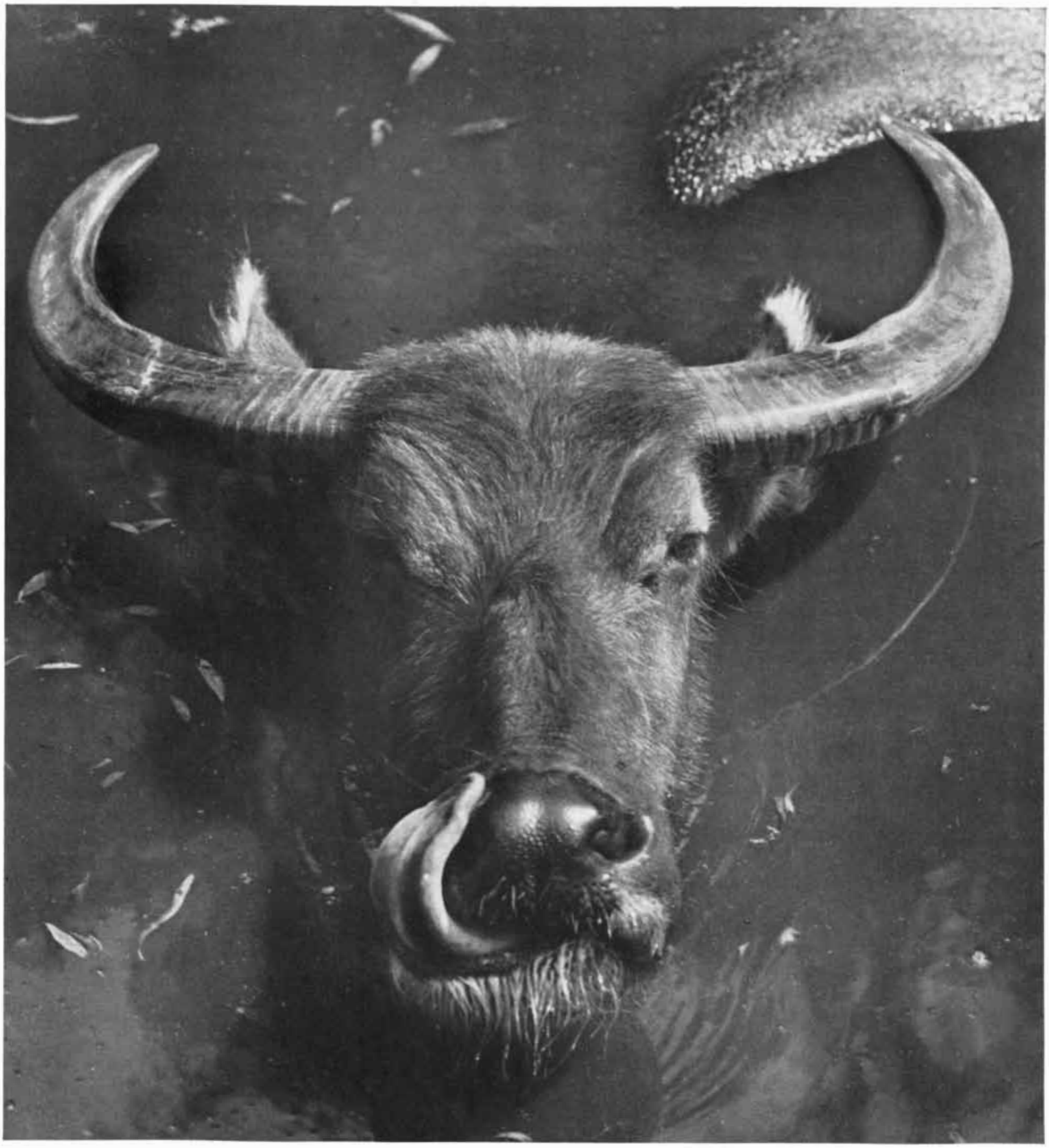
The swamp buffalo is the animal par excellence for the complex labors of the padi fields. As a domestic animal it is a single breed that closely resembles the Arni, or wild buffalo, of India and South China (from which all breeds of the water buffalo are supposed to have originated). Variants of the swamp buffalo range from the massive Thai buffalo, which weighs upward of 2,000 pounds, to the small carabao of the Philippines, which averages about 900 pounds. Even in limited geographical areas it varies widely in size. The swamp buffalo is normally slate black, having a dark skin and a sparse coat of black or gray hair. Below its jaw is a white chevron of unpigmented skin and hair; this marking is repeated lower down on the chest. Such stripes are peculiar to the swamp buffalo, the Surati breed of river buffalo and certain wild breeds, among them the Arni of India. Occasionally the hair of an animal will be tinged with red. White buffaloes, which have a pink skin and white or yellowish hair, are quite common. They are not true albinos; some pigment is present in their eyes, horns, hooves and mouth tissues. The whiteness appears to be a recessive hereditary characteristic. Probably about 5 percent of all the swamp buffaloes are white; in some areas—for example northern Thailand—the white buffaloes account for as much as 30 percent of the buffalo population.

In hot climates swamp buffaloes must have almost unlimited access to water. Buffaloes are not noticeably tolerant of heat, and they can suffer extreme discomfort if they are exposed for any length of time to the direct rays of the sun. They need to wallow uninterruptedly during the heat of the day. Few animals convey an impression of such blissful contentment as a swamp buffalo immersed to the nostrils in a mud wallow or standing ecstatically in a downpour of tropical rain.

In China and India the water buffalo has a particularly long history. The river buffalo is known to have been domesticated in India by 2500 B.C. and the swamp buffalo in China about 1,000 years later. From these two centers buffaloes have spread around the world. Their migration has not, however, been rapid; most of it appears to have taken place during comparatively recent times. In Egypt, for example, there are now as many buffaloes as there are cattle (well over 1.5 million), but buffaloes do not appear in the paintings and frescoes of the pharaohs' tombs. Introduction of the animal seems to have been delayed until about A.D. 800. Even in Cambodia, which is in the heart of buffalo territory, the animal may not have arrived in any numbers until the 15th century. At that time the Cambodian Khmer civilization fell to the Thai conquerors, who were very likely utilizing large numbers of swamp buffaloes for draft purposes.

It is estimated that there are in the world today about 100 million buffaloes. This may well be a considerable underassessment, since accurate totals are not available for many of the 20-odd countries where buffaloes are plentiful. The buffalo thrives in many places where it is truly exotic. There are at least 40,000 of the animals in Italy, where they supply the milk for mozzarella cheese. Brazil has almost 70,000. Ranchers on the island of Marajó in the Amazon delta consider the animal more productive than any other in that environment, where widespread flooding is common and marshy conditions prevail. Hong Kong has an indigenous population of about 2,000 small, sturdy swamp buffaloes, and it imports many thousands a year from China and other countries for slaughter.

Not all attempts to introduce the buffalo have been successful. The animal was brought to England by the Earl of Cornwall, the brother of Henry III, but it did not flourish. Efforts have been made for five centuries to establish buffaloes in African countries south of the Sahara, but usually the animal has died out. A more spectacular failure occurred in Australia, where buffaloes were introduced in the first half of the 19th century. Perhaps due to a lack of proper managerial skills—the animal is nervous



WATER BUFFALO WALLOWS in a pool of muddy water. Wallowing is a necessity for water buffaloes in hot climates; they cannot tolerate exposure to the direct rays of the sun. The animal's horns are a formidable defense but are seldom used in attack.

BUFFALOES PULL A HARROW across a flooded padi, or rice, field in Indonesia. Between the padi fields are bunds, or low mud walls. One advantage of the water buffalo is that it is able to walk securely in mud and step over the bunds without damaging them.

with strangers and does not adapt easily to European handlers—large numbers of the imported buffaloes were allowed to become feral. Today in the Northern Territory of Australia there are perhaps 200,000 "wild" swamp buffaloes.

In their native Eastern environment buffaloes are tractable; indeed, it is this characteristic that basically accounts for their domestication. They are difficult to herd or drive but easy to lead; they seldom kick or use their massive horns for attack. In many countries buffaloes are customarily handled by small children. It is a common sight to see children leading or riding these enormous beasts to wallowing places, lying at full length on their backs, getting into the water with them, washing them down, cleaning their ears and eyes and nostrils with care and complete fearlessness. This same imperturbable docility makes the buffalo an ideal animal for the slow, plodding work of the padi fields. Its sureness of foot, due to an unusual flexibility of the fetlock and pastern joints above its large cloven hoof, enables it to step carefully over the bunds: the low mud walls that bound each padi field. So easy is the animal to guide that usually the only means of controlling it is a single rein fastened to a nose thong or even looped casually around the great horns.

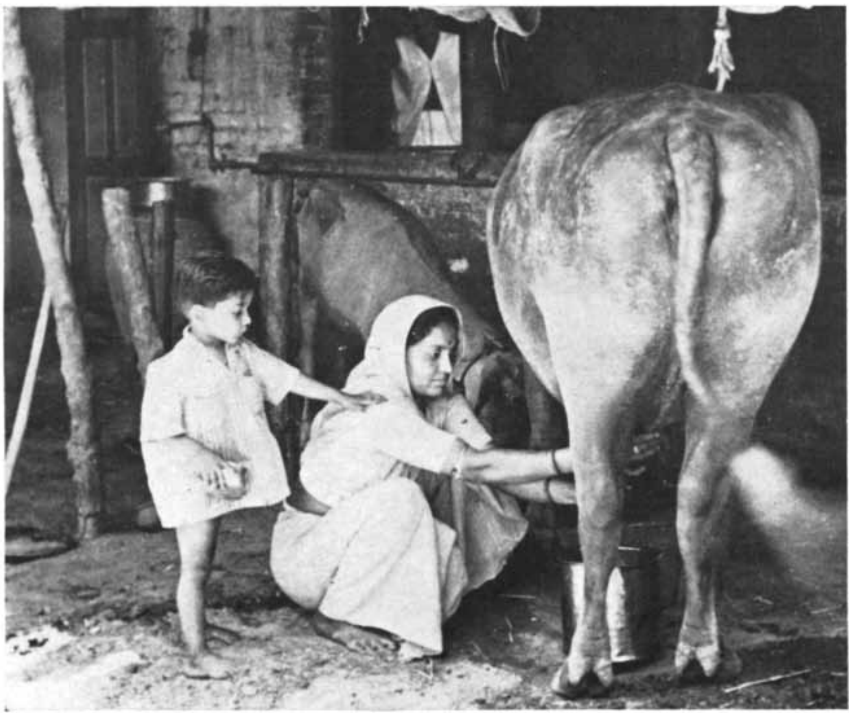
All breeds of the buffalo have horns. They vary in size and conformation from the heavy, backswept horns of the swamp buffalo to the tightly curled ones of the Murrah breed. The fact that the animals are rarely polled purposely is in itself a sufficient comment on the danger of the horns. In some countries buffaloes may have to defend themselves against tigers and other predators, and their horns can provide a formidable defense. The animals do not as a rule fight among themselves. When they do, it is likely to be a sort of pushing match, more a trial of strength than a sustained battle. On occasion, however, they will fight to the death and can only be dissuaded by tossing bundles of burning straw between them.

Buffaloes of all breeds are competent work animals where speed is not an essential requirement. In the rice-growing lands they are used to plow the soil and, when the fields have been flooded, to harrow and puddle the lumpy earth to the proper consistency for planting the rice shoots. They work with ease hock-deep in liquid mud. Often the buffaloes are rested between planting and harvest by being turned out to open forest land to fend for themselves. The owner of a buffalo has no difficulty recognizing it at harvest time, when it is reclaimed and put to work pulling sheaves to the threshing floor in carts or light bamboo sledges.

The buffalo is widely employed in most Eastern countries in a primitive but surprisingly effective system of threshing rice. A rattan mat is laid over a baked mud floor and sheaves are loaded onto it with pitchforks. Then two, three or more buffaloes plod in a tight circle, trampling the grain from the stalks as the herdsman forks the rice stalks under their hooves.

Buffaloes still operate simple mills that express oil from seeds and juice from sugarcane. In India, along with oxen and camels, they raise water from wells and, by involved irrigation systems,

BUFFALOES DRAW A HEAVY LOAD to a cotton mill in Pakistan. Each crude two-wheeled cart carries nearly a ton of cotton. Bells hanging from the neck of the buffaloes warn of their approach; the carts have no brakes and a sudden halt is impossible. The tightly curled horns of the animals identify them as river buffaloes of the Murrah breed.



BUFFALO IS MILKED by a woman of India, where more than half of the milk supply is furnished by water buffaloes. Water buffalo milk is twice as rich in butterfat as cattle milk.

send it coursing down shallow channels. Sometimes the large bucket in which the water is raised is made out of buffalo hide.

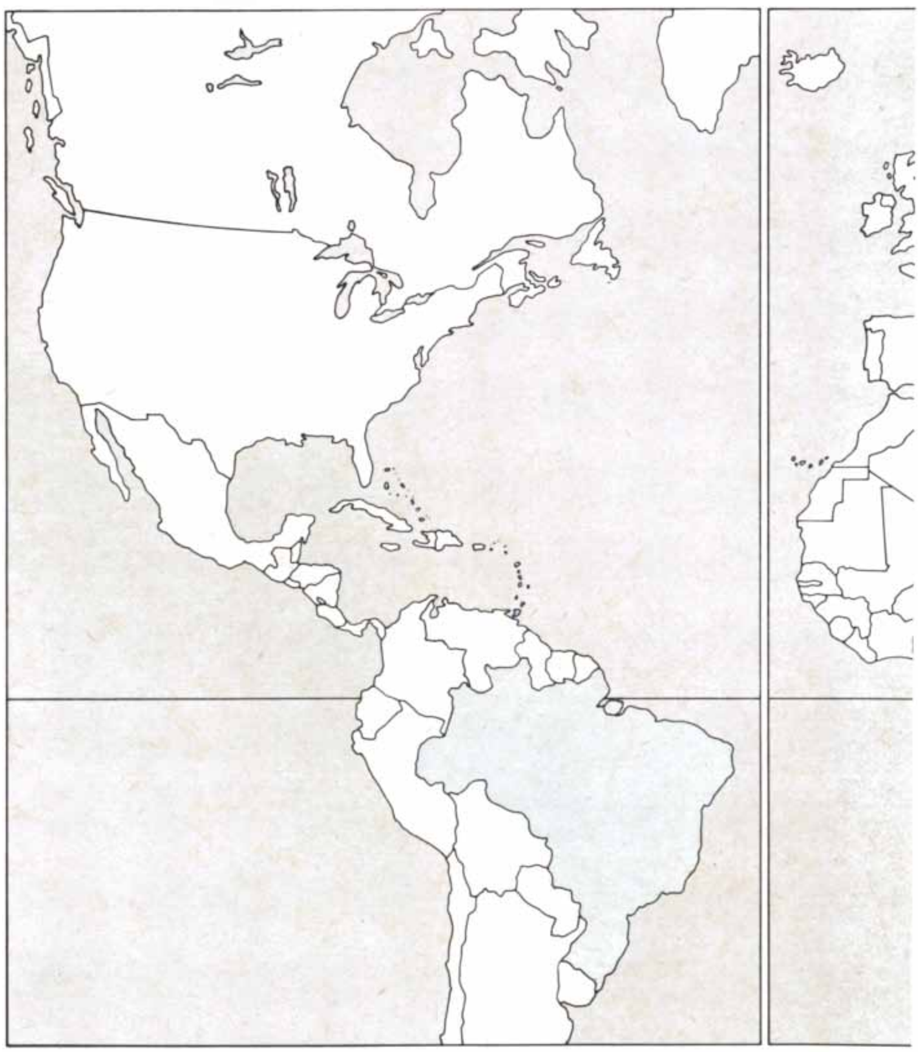
Crude two-wheeled carts drawn by one or two buffaloes can move heavy loads, again where speed is not important. In the crowded bazaar areas of cities such as Peshawar in Pakistan and Calcutta, Ahmadabad and Madras in India, buffaloes drag their heavy loads through teeming crowds with ponderous imperturbability. The bells that hang from the animals' necks give warning of their approach, and it is well to get out of their way. With a load of a ton or more and a cart that has no brakes a sudden pull-up is impossible.

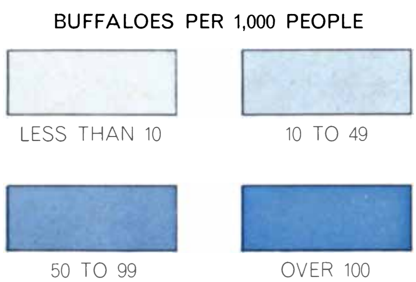
In Ceylon and a few other countries where buildings of mud brick or wattle-and-daub are still common, water buffaloes are used to puddle clay to the correct consistency. The buffalo can be used as a riding animal and as a pack animal. In Taiwan the traffic halts on a main highway to allow the passage of a buffalo train—four loaded trucks drawn by a plodding buffalo on a narrow-gauge line.

No source of power is quite as cheap as buffalo power. Rice is the staple food of half the world's population, and in the immemorial pattern of padi production the buffalo is an integral part of the slow, meticulous, backbreaking monotony of the struggle for existence. It is with justification that the animal is called the living tractor of the East. Where time is of little consequence, the buffalo can be turned out to pasture between planting and harvest and still be a profitable animal. Tractors, like most other machines, are economic only as long as they are in continual use. Alternating periods of activity and rest are feasible for the living tractors but not for the rust-prone variety.

It is in India and as a source of milk that the buffalo is seen to greatest advantage. It is responsible for more than half of the milk produced in that country. Buffalo milk contains about twice as much butterfat as cattle milk. On occasion the fat content may be as high as 15 percent; the overall average is probably 7 percent or a little more. The nonfat-solid content compares well with that of cattle milk, varying between about 9 and 10.5 percent. Depending on the breed and on management practices the daily milk yield of a buffalo ranges from the two to four quarts produced by an actively working draft female to the occasional 16 quarts of an exceptional dairy animal. Although buffaloes usually yield less milk than cattle maintained under similar conditions, the product for general purposes is as good as cattle milk and for certain purposes is much better. The buffalo is the main source of ghee, a dehydrated and clarified form of butter that is as widely used for cooking in India as olive oil is in the Mediterranean countries. Because the milk is so rich it lends itself to judicious dilution. When powdered skim milk and water are added, the resulting product is attractive and palatable. A rich and nutritious yogurt is made from buffalo milk, as are candy and excellent ice cream. In the Philippines, where the working swamp buffalo is also used as a dairy animal, the milk is made into a soft cheese.

A number of cooperative dairy farms have been formed in India. The Haringhata farm, which is near Calcutta, has in addition to cattle 3,500 buffaloes; it professes to be the largest dairy farm in the world. Another enterprise, located at Anand in the state of Gujarat, is one of the most remarkable of all cooperative movements. It is the Kaira District Cooperative Milk Producers' Union Ltd., managed by V. Kurien together with a





WORLD DISTRIBUTION of water buffaloes (which total about 100 million) indicates that they are most plentiful in South Asia and exist in appreciable numbers as far afield as Europe and Brazil. The animal flourishes on ranches in the Amazon valley. In Italy

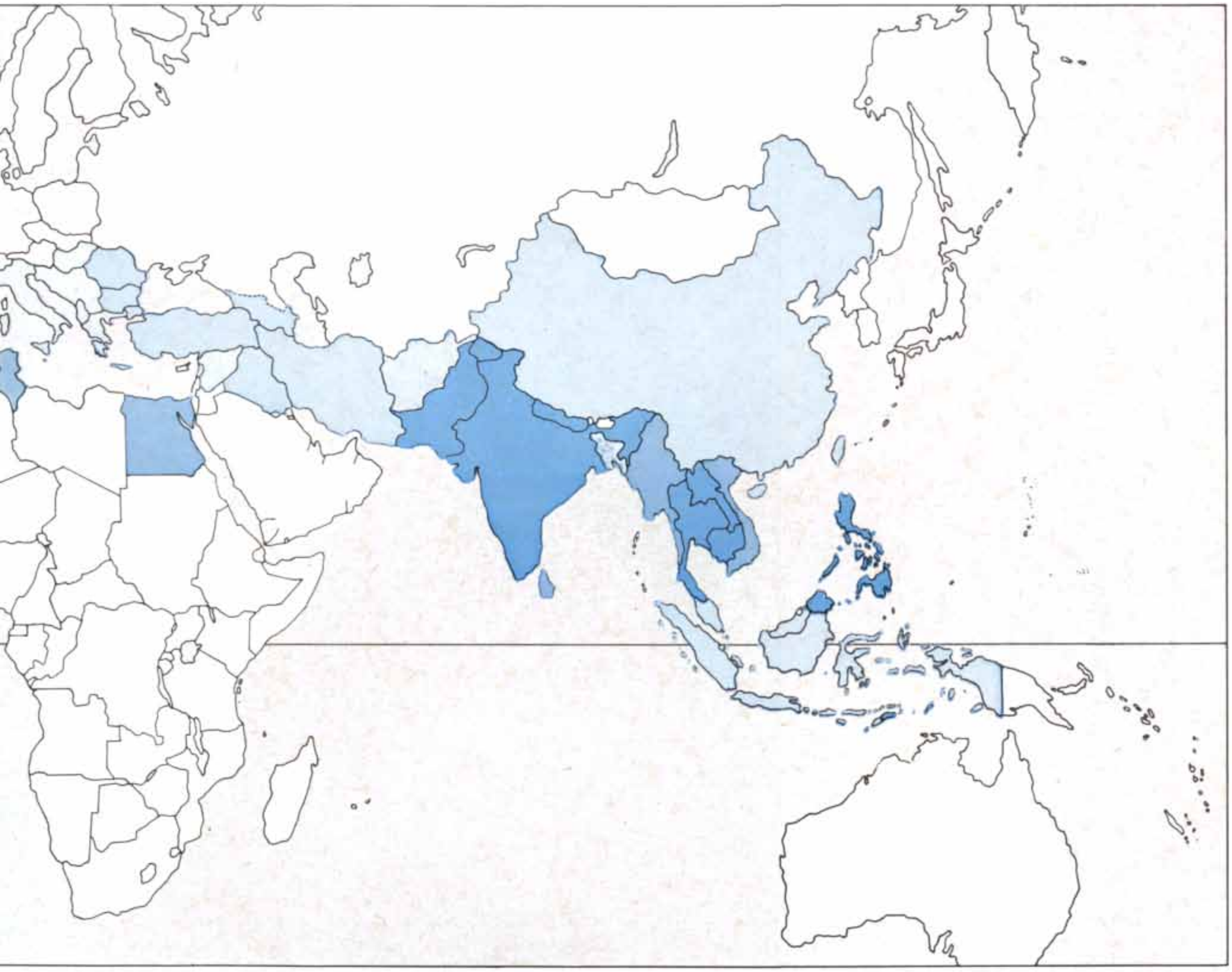
team of specialists in nutrition, breeding and health. If India had a hundred cooperatives like this one, the world would hear less of food crises and famines. More than 80,000 farmers in some 500 villages make up the cooperative. The usual holding is no bigger than three acres. It supports a family of five owning two or three buffaloes (of the Surati breed) and possibly also several cattle. The Surati are favored for their docility and for their ability to convert rough fodder into rich milk. The men tend the cattle, but the care of the buffaloes is entrusted exclusively to the women and children. Each day the cooperative sends 200,000 pounds of buffalo milk to Bombay in rail tankers donated to the cooperative by New Zealand. In addition, its milk-processing plant can produce sizable quantities of butter, condensed milk, ghee, cheese, casein, dried milk powder and baby food. Besides health and breeding services for the animals, the cooperative supports schools, libraries and hospitals. It demonstrates what can be done when basic principles of nutrition, breeding and health control are applied to the management of buffaloes.

In its reactions to disease the water buffalo is an enigma. It is highly susceptible to certain infections and notably resistant to others. To rinderpest, hemorrhagic septicemia, anthrax and foot-and-mouth disease buffaloes are even more susceptible than cattle, or so it often appears. Yet the degree of susceptibility varies, and it should be noted that one of the principal reasons for the survival of the animal in Egypt is its resistance to rinderpest, which in the past has decimated the cattle population. Complicating the problem is the fact that some vaccines producing a satisfactory degree of immunity in cattle initiate a poor antibody response in buffaloes.

The great famines that have occurred in the East, some of them within living memory, have been supported, perhaps sometimes even started, by outbreaks of disease among livestock. Since the buffaloes are a mainstay of rice production, when a killing disease such as rinderpest or a crippling one such as foot-and-mouth disease strikes at the time of planting or harvest, there is no source of draft power save man himself.

Mastitis and tick-borne diseases are much less common in buffaloes than in cattle, but the incidence of tuberculosis varies. In some parts of India buffaloes have been found to be more heavily infected than cattle. Heavy parasitic infestations—for example liver fluke—are common in buffaloes.

The gaps in our knowledge of this animal become most obvious when we



it provides milk for mozzarella cheese; there and in Bulgaria and Yugoslavia it is also reared for meat. The water buffalo has been introduced into England, France, Germany, Spain, South Africa and Australia, but for various reasons it did not become established.

consider it as a meat producer. In many of the lands of the buffalo millions of people are vegetarian from choice, religious conviction or sheer economic necessity. Cereals are all-important in these areas, and the production of animal protein for human consumption is low on the list of priorities. Many countries prohibit the slaughter of buffaloes younger than 12 years of age, except when they are infertile, intractable or incapable of work. An enormous waste results from the practice of depriving some calves of the commercially valuable milk and allowing them to starve to death. Tens of thousands of calves representing a potential source of high-quality veal are thus lost.

The widespread ban in India on the slaughter of sacred cows does not apply to buffaloes; however, in India and elsewhere the buffalo is accorded an extraordinary degree of care and consideration. It is treated almost as a member of the family. Indeed, the animal is as important as a member of the family in the contribution it makes to the family's welfare. So narrow can be the margin between subsistence and starvation that the loss of a single buffalo can be disastrous.

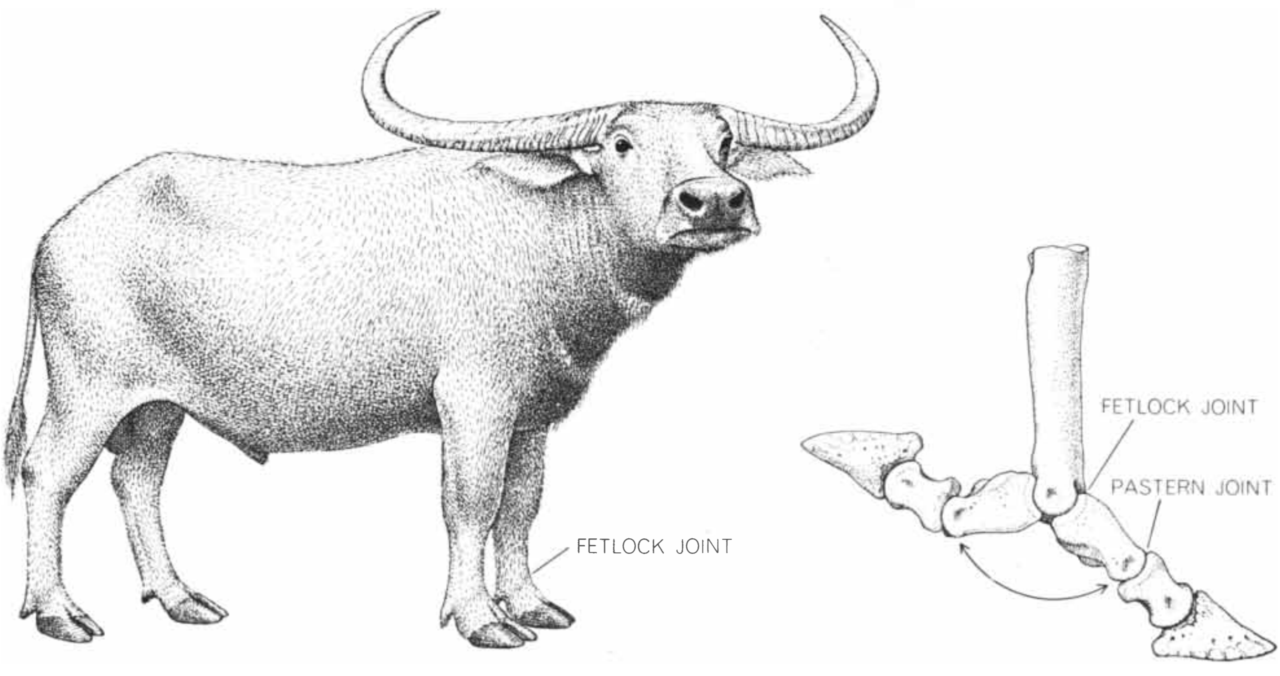
The water buffalo is remarkable for its longevity. Instances are quite often cited of animals living to the age of 40, and it is common to find buffaloes still working at 20. When the pace of the buffalo slows below the level at which the animal is economic to maintain, its owner—particularly in Buddhist countries—will often refuse to slaughter it and salvage something in meat value. The buffalo is allowed to live in peaceful retirement until death overtakes it.

In the East buffalo meat is generally a by-product. The animal is slaughtered only after years of labor or milk production or both. Abattoir facilities in developing countries tend to be inadequate: killing methods are clumsy, the meat is poorly butchered and handled and it is usually sold without being properly aged. If the buffalo were treated as a meat-producing animal and reared for slaughter at less than two years, meat of excellent quality could be obtained. The weight of the dressed carcass is usually 45 to 47 percent of the live weight, but in Italy, Bulgaria and Yugoslavia, which are among the few countries where the buffalo is reared for meat, a dressed carcass weight of 51 percent is not uncommon. The quality of the meat is good, and its flavor is generally indistinguishable from that of beef, although it is somewhat coarser in appearance. The fat, due to the absence of the pigment carotene, is pure white.

In parts of Nepal and Thailand the hide of the buffalo is eaten. It is cut into small strips and after prolonged boiling is dried in the sun and stored. When it is cooked in deep fat, it makes delicious "buffalo chips" that might well find a market in the West.

The hide makes excellent leather for shoe soles, belts or any other purpose where a thick, tough product is required. Reins and lassos are made from strips of buffalo hide that have been twisted, woven and softened with fat. They are prized possessions and are handed down from father to son. With modern machinery the hides can be split to yield a thin, strong product that when it is processed and dyed compares favorably with any other type of leather.

If modern methods of selective breeding were widely applied to the water buffalo, in place of the haphazard breeding and crossbreeding that obtain almost everywhere it is found, the potential of the buffalo could be realized. The buffaloes of Thailand are bigger and stronger than those of almost any other country. This is probably due to the fact that a system of selective breeding has been practiced there for many years. The best of the male animals are bought by the government, which sells or lends them to the villages for breeding purposes.



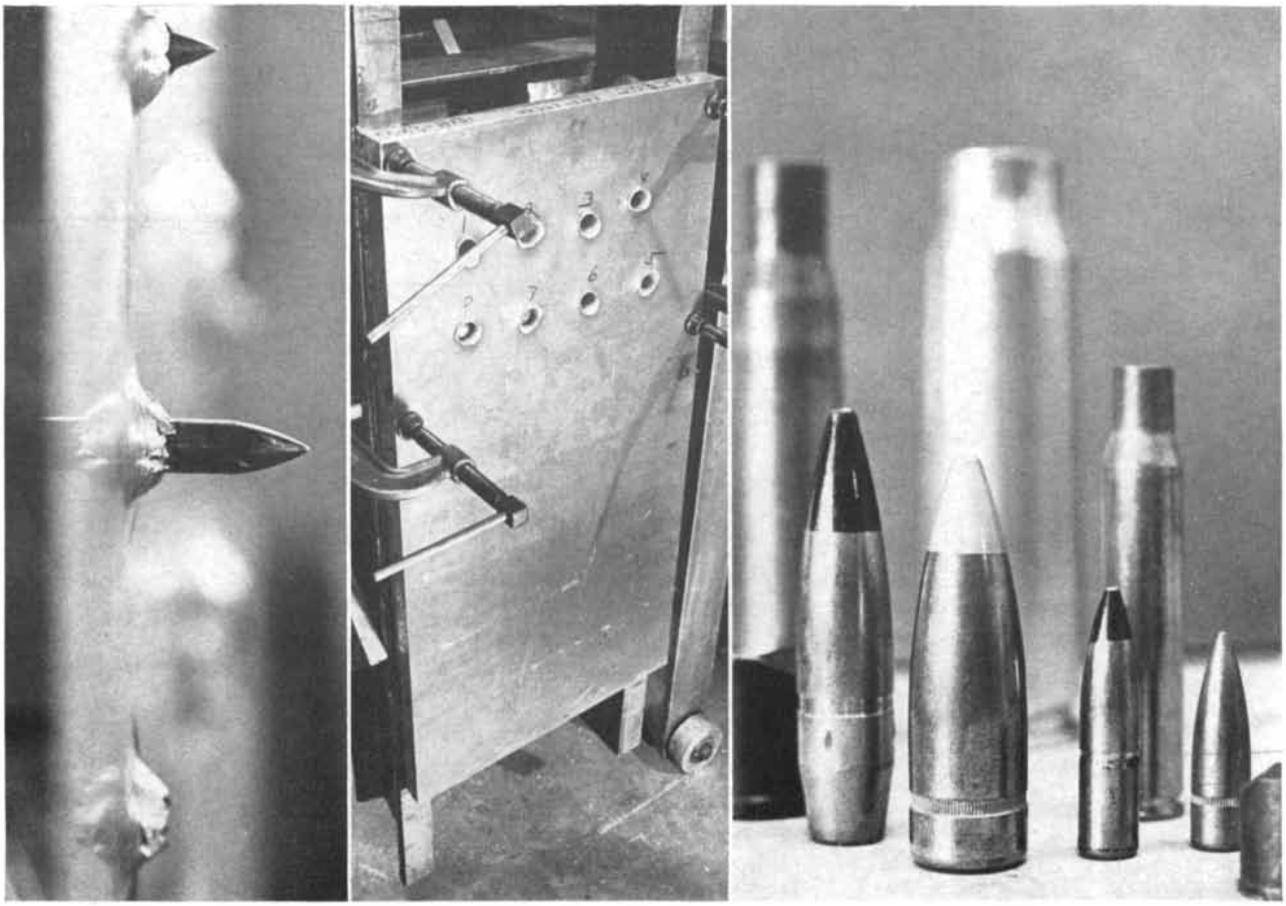
A MAJOR BREED of water buffalo is the swamp buffalo (*left*). All other domestic breeds are classified as river buffaloes. Both the swamp buffalo and river buffaloes are of the species *Bubalus bubalis*. The swamp buffalo varies widely in size but can weigh more than 2,000 pounds. Its fetlock and pastern joints (*right*) are exceptionally flexible, which is what enables the animal to move easily in mud. Swamp buffaloes are distinguished by heavy backswept horns and two white chevrons on the chest. They are sometimes confused with the wild buffalo of Africa (*Syncerus caffer*) and the American bison (*Bison bison*), but are not closely related to either of them.

The buffalo is a sluggish and seasonal breeder. With good management a calf every year is possible; two in three years is normally the case. Sexual activity is seldom seen; under natural conditions mating commonly takes place in the dusk or dark. Under modern management, however, the animal's breeding behavior is similar to that of cattle, although artificial insemination procedures call for certain adjustments. Estrus in buffaloes can be regulated by controlling the temperature of the building in which they are housed and also the degree of their exposure to light. If such procedures were instituted, it would be possible to reduce seasonal fluctuations in breeding that result in a majority of calves being born in the last quarter of the year, which of course gives rise to alternating periods of glut and scarcity in milk.

Even under the prevailing conditions of haphazard breeding, inept management and casual nutrition the buffalo is an outstandingly productive animal. It apparently has a unique ability to digest and assimilate the poorest of roughage. It is quite common to see buffaloes and cattle grazing together during the dry season in pastures where one would say there was barely enough sustenance to maintain life. The buffaloes will be in good condition, the cattle thin to the point of emaciation. Padi straw is the buffalo's staple diet. Dairy buffaloes receive extra feed in the form of concentrates and cut green herbage, when they are available, but the animal is able to work and to produce milk on the poorest of diets.

It is unfortunate that cattle protagonists are often violently antibuffalo; there is a place for both animals in this hungry world, and it is probable that in tropical and subtropical countries the buffalo has a greater protein potential than cattle. Countries in the Temperate Zone that have no buffaloes and that could provide the requisite management skills and quarantine security might usefully consider introducing some of the animals from selected areas on an experimental basis.

The buffalo has been profoundly important to the agricultural economy of bygone civilizations. Given the necessary scientific support it can make an outstanding contribution to our own. It is not an obsolete or vanishing animal. It can take a big part in meeting the needs of the expanding human population for increased supplies of meat and milk, and for the working power to produce more food.



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MATHEMATICAL GAMES

Game theory is applied (for a change) to games

by Martin Gardner

Game theory, one of the most elegant and useful branches of modern mathematics, was anticipated in the early 1920's by the French mathematician Émile Borel, but it was not until 1926 that John von Neumann gave his proof of the minimax theorem, the fundamental theorem of game theory. On this cornerstone he built almost single-handedly the beautiful basic structure of game theory. His classic 1944 work, *Theory of Games and Economic Behavior*, written with the economist Oskar Morgenstern, created a tremendous stir in economic circles [see "The Theory of Games," by Oskar Morgenstern; SCIENTIFIC AMERICAN, May, 1949]. Since then game theory has developed into a fantastic amalgam of algebra, geometry, set theory and topology, with applications to competitive situations in business, warfare and politics as well as economics.

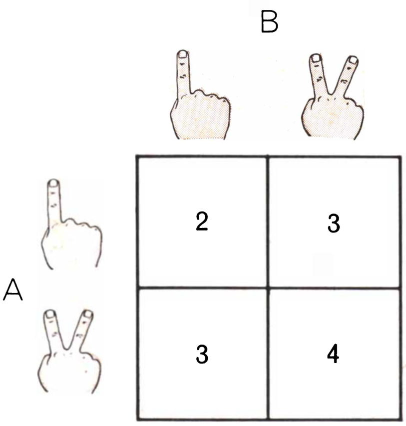
Attempts have been made to apply game theory to all kinds of other conflict situations. What is the nation's optimal strategy in the Cold War Game? Is the Golden Rule, some philosophers have asked, the best strategy for maximizing happiness payoffs in the Great Game of Life? How can a scientist best play the Induction Game against his formidable opponent Nature? Even psychiatry has not been immune. Although Eric Berne's "transactional therapy" (popularized by his best-selling *Games People Play*) makes no use of game theory mathematics, it borrows many of its terms and obviously has been influenced by the game theory approach.

Most game theory work has been on what are called two-person zero-sum games. This means that the conflict is between two players (if there are more, the theory gets muddied by coalitions) and whatever one player wins the other loses. (One reason game theory is difficult to apply to international conflicts is that they are not zero-sum; a loss for the U.S.S.R. is not necessarily a gain for the U.S., for example.) The main purpose of this month's department is to introduce a charming two-person zero-sum card game invented by Rufus Isaacs, a game theory expert who wrote *Differential Games* (John Wiley, 1965) and is professor of applied mathematics at Johns Hopkins University. But first a quick look at some elementary game theory.

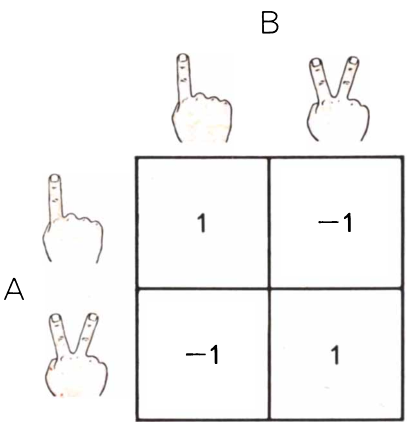
Consider this trivial game. Players *A* and *B* simultaneously extend one or two fingers, then *B* gives *A* as many dollars as there are fingers showing. The game obviously is unfair since *A* always wins. How, though, should *A* play so as to make his wins as big as possible, and how should *B* play so as to lose as little as possible? Most games have numerous and complicated strategies, but here each player is limited to two: he can show one finger or he can show two. The "payoff matrix" can therefore be drawn on a 2-by-2 square as shown in the illustration at the left below. By convention, *A*'s two strategies are shown on the left and *B*'s two strategies are shown above. The cells hold the payoffs for every combination of strategies. Thus if *A* shows one finger and *B* two, the intersection cell shows a $3 payoff to *A*. (Payoffs are always given as payments from *B* to *A* even when the money actually goes the other way, in which case the payment to *B* is indicated by a minus sign.)

If *A* plays one finger, the least he can win is 2. If he plays two fingers, the least he can win is 3. The *largest* of these lows (the 3 at lower left) is called the maxmin (after maximum of the minima). If *B* plays one finger, the most he can lose is 3. If he plays two fingers, the most he can lose is 4. The least of these highs (again the 3 at lower left) is called the minmax (minimum of the maxima). If the cell that holds the minmax is also the cell that holds the maxmin, as it is in this case, the cell is said to contain the game's "saddle point" and the game is said to be "strictly determined." Each player's best strategy is to play a strategy that includes the saddle point. *A* maximizes his gain by always showing two fingers; *B* minimizes his loss by always showing one. If both play their best, the payoff each time will be $3 to *A*. This is called the "value" of the game. As long as either player uses his optimal strategy he is sure to receive a payoff equal to or better than the game's value. If he plays a nonoptimal strategy, there is always an opposing strategy that will give him a poorer payoff than the value. In this case the game is of course so trivial that both optimal strategies are intuitively obvious.

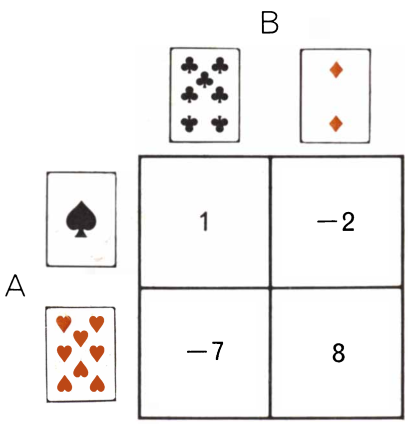
Not all games are strictly determined.



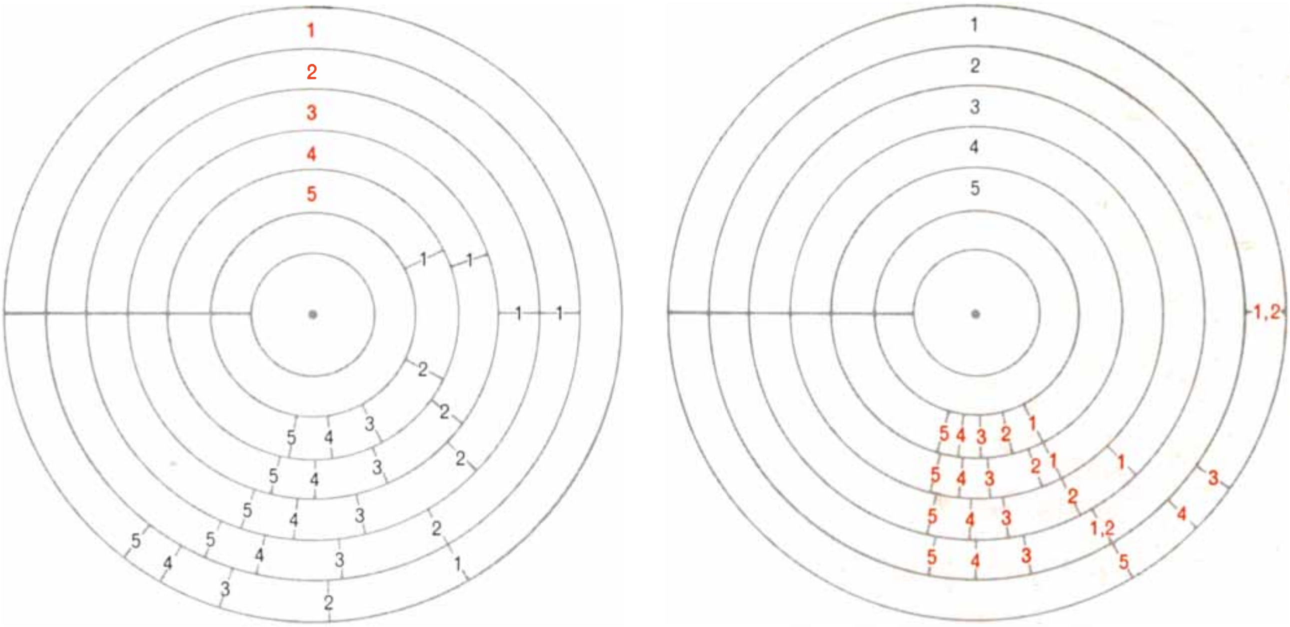
Payoff matrix for a trivial game



Matrix for odds-and-evens game



Matrix for card game



Randomizing dials for deciding when to bluff (left) *and when to call* (right)

If we turn the finger game into "odds and evens" (equivalent to the game of matching pennies), the payoff matrix becomes the one shown in the middle illustration on the preceding page. When fingers match, *A* wins \$1; when they do not match, *B* wins \$1. Since *A*'s maxmin is -1 and *B*'s minmax is 1, it is clear there is no saddle point. Consequently neither player finds one strategy better than the other. It would be foolish, for example, for *A* to adopt the strategy of always showing two fingers because *B* could win every time by showing one finger. To play optimally each player must mix his two strategies in certain proportions. Ascertaining the optimal proportions can be difficult, but here the symmetry of this simple game makes it obvious that they are 1 : 1.

This introduces an all-important aspect of game theory: to be effective the mixing must be done by a randomizing device. It is easy to see why nonrandom mixing is dangerous. Suppose *A* mixes by alternating one and two fingers. *B* catches on and plays to win every time. *A* can adopt a subtler mixing pattern but there is always the chance that *B* will discover it. If he tries to randomize in his head, unconscious biases creep in. When Claude E. Shannon, the founder of information theory, was at the Bell Telephone Laboratories, he and his colleague D. W. Hagelbarger each built a penny-matching computer that consistently won against human players when they made their own choices by pressing one of two buttons. The computer analyzed its opponent's plays, detected nonrandom patterns and played accordingly. Because the two machines used different methods of analyzing plays, they were pitted against each other "to the accompaniment," Shannon disclosed, "of small side bets and loud cheering" [see "Science and the Citizen"; SCIENTIFIC AMERICAN, July, 1954]. The only way someone playing against such a machine can keep his average payoff down to zero is to use a randomizer—for example, flipping a penny each time to decide which button to push.

The game matrix shown in the illustration at the right on the preceding page provides an amusing instance of a game with a far from obvious mixed strategy. Player *A* holds a double-faced playing card made by pasting a black ace back to back to a red eight. Player *B* has a similar double card: a red two pasted to a black seven. Each chooses a side of his card and simultaneously shows it to the other. *A* wins if the colors match, *B* if they fail to match. In every case the payoff in dollars is equal to the value of the winner's card.

The game *looks* fair (has a value of zero) because the sum of what *A* can win $(8 + 1 = 9)$ is the same as the sum of what *B* can win $(2 + 7 = 9)$. Actually the game is biased in favor of *B*, who can win an average of \$1 every three games if he mixes his two strategies properly. Since 8 and 1, in one diagonal, are each larger than either of the other two payoffs, we know at once that there is no saddle point. (A 2-by-2 game has a saddle point if and only if the two numbers of either diagonal are *not* both higher than either of the other two numbers.) Each player, therefore, must mix his strategies.

Without justifying the procedure, I shall describe one way to calculate the mixture for each player. Consider *A*'s top-row strategy. Take the second number from the first: $1 - (-2) = 3$. Do the same with the second row: $-7 - 8 = -15$. Form a fraction (ignoring any minus signs) by putting the last number above the first: 15/3, which simplifies to 5/1. *A*'s best strategy is to mix in the proportions 5 : 1, that is, to show his ace five times for every time he shows his seven. A die provides a convenient randomizer. He can show his ace when he rolls 1, 2, 3, 4 or 5, his seven when he rolls 6. The randomizer's advice must, of course, be concealed from his opponent, who otherwise would know how to respond.

B's best strategy is similarly obtained by taking the bottom numbers from the top. The first column yields 8, the second -10. Ignoring minus signs and putting the second above the first gives 10/8, or 5/4. *B*'s best strategy is to show his seven five times to every four times for the two. As a randomizer he can use a table of random numbers, playing the seven when the digit is 1, 2, 3, 4 or 5 and the deuce when it is 6, 7, 8 or 9.

To calculate the game's value (the average payoff to *A*), assume that the cells are numbered left to right, top to bottom, *a, b, c, d*. The value is

$$\frac{ad - bc}{a + d - b - c}.$$

The formula in this case has a value of

−1/3. As long as *A* plays his best strategy, the 5 : 1 mixture, he holds his average loss per game to a third of a dollar. As long as *B* plays his best mixture, the 5 : 4, he ensures an average win per game of a third of a dollar. The fact that every matrix game, regardless of size or whether it has a saddle point, has a value, and that the value can be achieved by at least one optimal strategy for each player, is the famous minimax theorem first proved by von Neumann. Readers may enjoy experimenting with 2-by-2 card games of this type but using different cards, and calculating the game's value and optimal strategies.

Most two-person board games, such as chess and checkers, are played in a sequence of alternating moves that continues until either one player wins or the game is drawn. Since the number of possible sequences is vast and the number of possible strategies is astronomically vaster, the matrix is much too enormous to draw. Even as simple a game as ticktacktoe would require a matrix with tens of thousands of cells, each labeled 1, −1 or 0. If the game is finite (each player has a finite number of moves and a finite number of choices at each move) and has "perfect information" (both players know the complete state of the game at every stage before the current move), it can be proved (von Neumann was the first to do it) that the game is strictly determined. This means that there is at least one best pure strategy that always wins for the first or for the second player, or that both of the players have pure strategies that can ensure a draw.

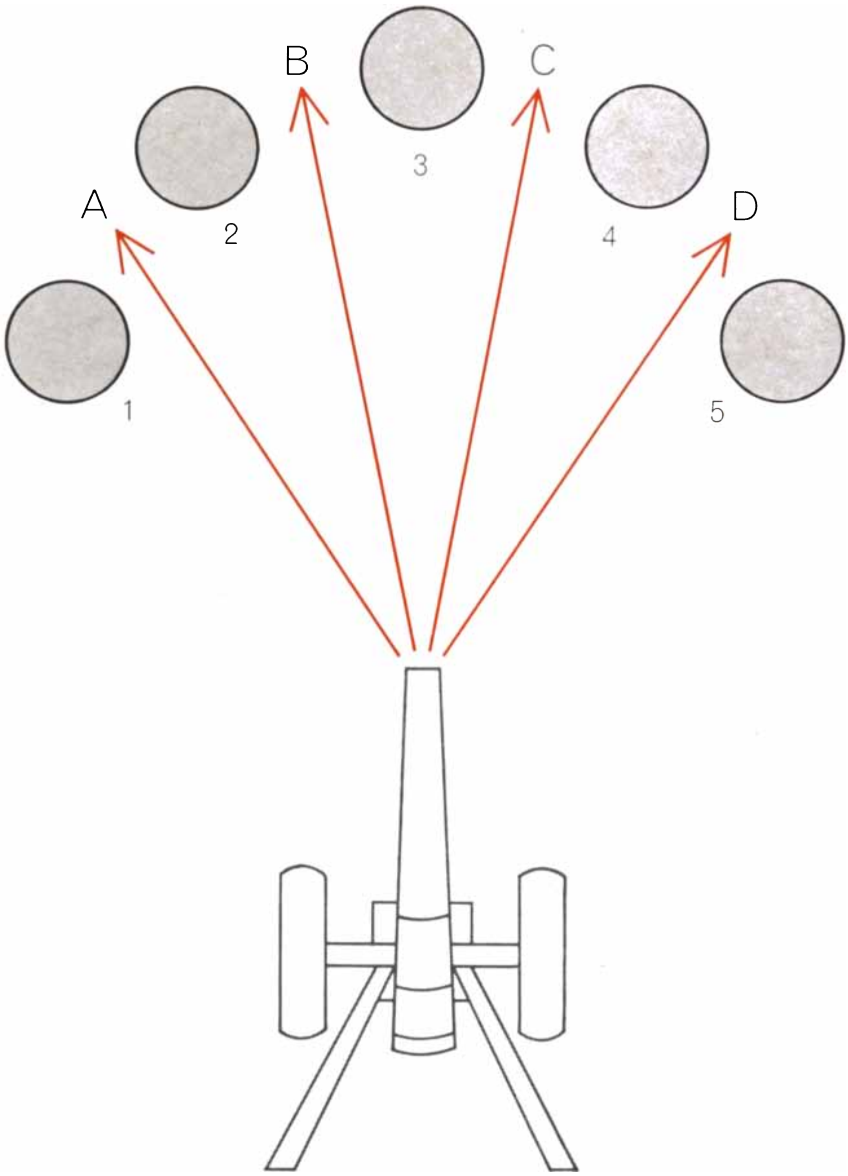
Almost all card games are of the sequential-move type but with incomplete information. Indeed, the purpose of making the backs of cards identical is to conceal information. In such games the optimal strategies are mixed. This means that a player's best decision on most or all of his moves can be given only probabilistically and that the value of the game is an average of what the maximizing player will win in the long run. Poker, for instance, has a best mixed strategy, although (as in chess and checkers) it is so complicated that only simplified forms of it have been solved.

Isaacs' card game, named Guess It by his daughter Ellen, is remarkable in that it is a two-person sequential-move game of incomplete information, sufficiently complicated by bluffing to make for stimulating play, yet simple enough to allow complete analysis.

The game uses 11 playing cards with values from ace to jack, the jack counting as 11. The packet is shuffled. A card

NUMBER OF CARDS IN OPPONENT'S HAND \ NUMBER OF CARDS IN PLAYER'S HAND	1	2	3	4	5
1	.5	.667	.688	.733	.75
2	.5	.556	.625	.648	.680
3	.4	.512	.548	.597	.619
4	.375	.450	.513	.543	.581
5	.333	.423	.467	.512	.538

Chart of probabilities of winning Guess It game



The foxhole game

is drawn at random and placed face down in the center of the table, neither player being aware of its value. The remaining 10 cards are dealt, five to each player. The object of the game is to guess the hidden card. This is done by asking questions of the form "Do you have such-and-such a card?" The other player must answer truthfully. No card may be asked about twice.

At any time, instead of an "ask" a player may end the game by a "call." This consists of naming the hidden card. The card is then turned over. If it was correctly named, the caller wins; otherwise he loses. To play well, therefore, a player must try to get as much information as he can, at the same time revealing as little as possible, until he thinks he knows enough to call. The delightful feature of the game is that each player must resort to occasional bluffing, that is, asking about a card he himself holds. If he never bluffed, then whenever he asked about a card not in his opponent's hand, the opponent would immediately know that card must be the hidden one—and would call and win. Bluffing is therefore an essential part of strategy, both for defense and for tricking the opponent into a false call.

If player *A* asks about a card, say the jack, and the answer is yes, both players will then know *B* has that card. Since it will not be asked about again, nor will it be called, the jack plays no further role in the game. *B* places it face up on the table.

If *B* does not have the jack, he answers no. This places him in a quandary, although one that proves to be short-lived. If he thinks *A* is not bluffing, he calls the jack and ends the game, winning if his suspicion is correct. If he does not call it and the hidden card *is* the jack, then *A* (who originally asked about it) will surely call the jack on his next play, for he will know with certainty that it is the hidden card. Therefore, if *A* does *not* call the jack on his next play, it means he had previously bluffed and has the jack in his hand. Again, because the location of the card then becomes known to both players, it plays no further role. It is removed and placed face up on the table. In this way hands tend to grow smaller as the game progresses. After each elimination of a card the players are in effect starting a new game with fewer cards in hand.

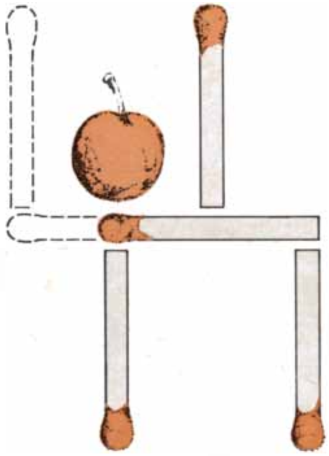
It is impossible to give here the details of how Isaacs solved the game. The interested reader will find it explained in his article "A Card Game with Bluffing" in *The American Mathematical Monthly* (Vol. 62, February, 1955, pages 99–108). I will do no more here than explain the optimal strategies and how they can be played with the aid of two spinners made with the dials shown in the illustration on page 128. Readers are urged first to play the game without these randomizers, keeping a record of *n* games between players *A* and *B*. They should then play another *n* games with only *A* using the spinners, followed by a third set of *n* games with only *B* using the spinners. (If both players use randomizers, the game degenerates into a mere contest of chance.) In this way an empirical test can be made of the efficacy of the strategy.

The dials can be copied or mounted on a rectangle of stiff cardboard. Stick a pin in the center of each and over each pin put the loop end of a bobby pin. A flip of the finger sends the bobby pin spinning. The spinners must of course be kept out of your opponent's view when being used, either by turning your back when you spin them or keeping them on your lap below the edge of the table. After using them you must keep a "poker face" to avoid giving clues to what the randomizers tell you to do.

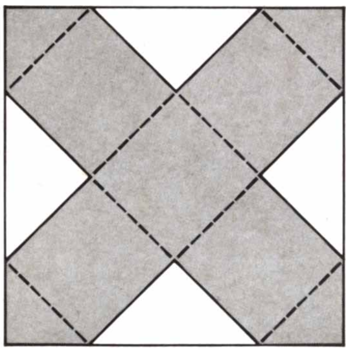
The first dial tells you when to bluff. The colored numbers give the number of cards in your hand. The black numbers scattered over the dial and attached to marks stand for the number of cards in your opponent's hand. Assume that you have three cards and he has two. Confine your attention to the ring labeled with a colored 3. Spin the bobby pin. If it stops in the portion of the ring that extends clockwise from mark 2 to the heavy horizontal line, you bluff. Otherwise you ask about a card that could be in your opponent's hand.

In either case, asking or bluffing, pick a card at random from the possibilities open to you. If a strict empirical test of strategy is to be made, you should use a randomizer for this selection. The simplest device would be a third spinner on a circle divided into 11 equal sectors and numbered 1 to 11. If the first spinner tells you to bluff, for example, and you have two, four, seven and eight in your hand, you spin the third spinner repeatedly until it stops on one of those numbers. Without the aid of such a spinner, simply select at random one of the four cards in your hand. The danger of your opponent's profiting from an unconscious mental bias is so slight, however, that we shall assume a third spinner is not used.

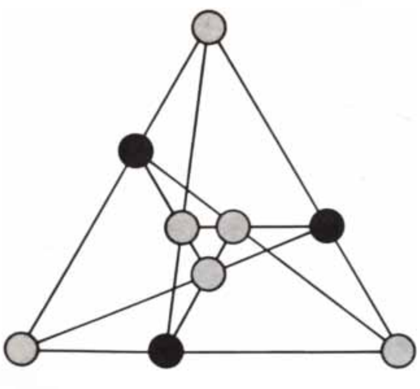
The second dial is used whenever you have just answered no to an ask. On this dial the rings are labeled with black numbers to indicate that they correspond to the number of cards in your opponent's hand. The colored numbers near the marks give the number of cards you hold. As before, pick the appropriate ring and spin the bobby pin. If it stops in the portion of the ring that extends from the proper mark clockwise to the horizontal line, call the card previously asked. If it does not stop in this portion of the ring, your next action depends on whether your opponent has just one card or more than one. If he has only one, call the other unknown card. If he has more than one (and you have at least one



Solution to match problem



Cube-folding solution



Tri-Hex solution

card), you must ask. To decide whether to bluff or not, spin the first dial, but now you must pick your ring on the assumption that his hand is reduced by one card. The reason for this is that if he did not bluff on his last ask, your "No" answer will enable him to win on his next move. You therefore play as if he were bluffing and the game were to continue, in which case the card he asked about has been taken out of the game by your "No" answer even though it is not actually placed face up on the table until after his next move.

In addition to the circumstances just explained, you call only under the following circumstances: 1. When you know the hidden card. (This occurs when you have asked without bluffing and received a "No" reply, and he has not won the game by calling on his next turn; and it occurs of course when he holds no cards.) 2. When you have no cards and he has one or more, because if you do not call, he surely will call and win on his next play. If each of you holds just one card, it is immaterial whether you call or ask; the probability of winning is 1/2 and is obtained either way. 3. When instructed to call by the second dial, as explained before.

The table at the top of page 129 shows the probability of winning for the player who has the move. The number of his cards appears at the top, those of the other player on the left. At the beginning, assuming that both players use randomizers for playing their best, the first player's probability of winning is .538, or slightly better than 1/2. If the payoff to the first player is $1 for each win and zero for each loss, then $.538 is the value of the game. If after each game the loser pays the winner $1, the first player will win an average of 538 games out of every 1,000. Since he receives $538 and loses $462, his profit is $76, and his average win per game is $76/1,000, or $.076. With these payoffs the game's value is a bit less than eight cents per game. If the second player does not use randomizers, the first player's chance of winning increases substantially, as should appear in an empirical test of the game.

As a problem to be answered next month, here is a simple, idealized war game that Isaacs uses to explain mixed strategies to military personnel. One player, the soldier, has a choice of hiding in any one of the five foxholes shown in the bottom illustration on page 129. The other player, the gunner, has a choice of firing at one of the four spots *A, B, C, D*. A shot will kill the soldier if he is in either adjacent foxhole—shot *B*, for example, is fatal if he is in foxhole 2 or 3.

"We can see the need for mixing strategies," Isaacs writes, "for the soldier might reason: 'The end holes are vulnerable to only one shot, whereas the central holes can each be hit two ways. Therefore I'll hide in one of the end holes.' Unfortunately the gunner might foresee this reasoning and fire only at *A* or *D*. If the soldier suspects that the gunner will do this, he will hide in a central hole. But now the gunner may still be one up by guessing that the soldier will think he will think this way, therefore he aims at the center. These attempts at outthinking the opponent lead only to chaos. The only way either player can be sure of deceiving his opponent is by mixing his strategies."

Assume that the payoff is 1 if the gunner kills the soldier, 0 if he does not. The value of the game is then the same as the probability of a hit. What are the optimal strategies for each player and what is the game's value?

Answers to last month's problems are as follows:

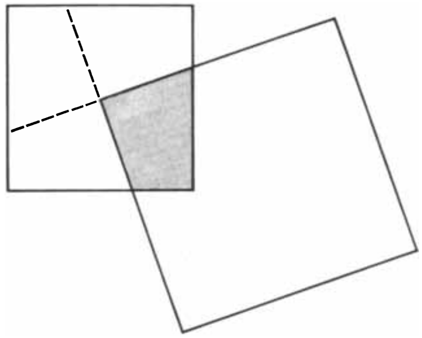
1. The top illustration on the opposite page shows how two matches are moved to re-form the cocktail glass with the cherry outside.

2. The largest cube that can be folded from a pattern cut from a square sheet of paper with a three-inch side is a cube with a side that is three-fourths of the square root of 2. The pattern, shown shaded in the middle illustration on the opposite page, is folded along dotted lines.

3. If each man at a circular table is either a truther or a liar, and each says that the man on his left is a liar, there must be an even number at the table, arranged so that truthers and liars alternate. (No arrangement of an odd number of truthers and liars is possible without at least one man describing the man on his left as a truther.) Consequently the club's president lied when he said the number was 37. Since the secretary sat next to the president, he must have been a truther, and therefore he spoke truthfully when he gave the number as 40.

4. We were told that the two brothers who inherited a herd of sheep sold each sheep for the same number of dollars as there were sheep. If the number of sheep is n, the total number of dollars received is n^2. This was paid in $10 bills plus an excess, less than 10, in silver dollars.

By alternately taking bills, the older brother drew both first and last, and so the total amount must contain an odd



The overlapping squares

number of 10's. Since the square of any multiple of 10 contains an even number of 10's, we conclude that n (the number of sheep) must end in a digit the square of which contains an odd number of 10's. Only two digits, 4 and 6, have such squares: 16 and 36. Both squares end in 6, and so n^2 (the total amount received for the sheep) is a number ending in 6. The excess amount consisted of six silver dollars.

After the younger brother took the $6 he still had $4 less than his brother, so to even things up the older brother wrote a check for $2. It is surprising how many good mathematicians will work the problem correctly up to this last step, then forget that the check must be two dollars instead of four.

5. Ticktacktoe on the Tri-Hex pattern [*see bottom illustration on opposite page*] is a win for the first player, but only if he plays first on one of the black spots. Regardless of his opponent's choice of a spot, the first player can always play so that his opponent's next move is forced, then make a third play that threatens a win on two rows, thereby ensuring a win on his last move.

If the opening move is on a corner of the board, the second player can force a draw by seizing another corner. If the opening move is on a vertex of the central equilateral triangle, the second player can force a draw by taking another corner of that triangle. For a more complete analysis see "New Boards for Old Games," by Thomas H. O'Beirne in *New Scientist* for January 11, 1962.

6. The unique solution to Langford's problem with four pairs of cards is 41312432. It can be reversed, of course, but this is not considered a different solution.

If n is the number of pairs, the problem has a solution only if n is a multiple of 4 or one less than such a multiple. C. Dudley Langford posed his problem in *The Mathematical Gazette* (Vol. 42, October, 1958, page 228). For subsequent discussion see C. J. Priday, "On Langford's Problem (I)," and Roy O. Davies, "On Langford's Problem (II)," both in *The Mathematical Gazette* (Vol. 43, December, 1959, pages 250–255); Frank S. Gillespie and W. R. Utz, "A Generalized Langford Problem," *Fibonacci Quarterly* (Vol. 4, April, 1966, pages 184–186), and R. S. Nickerson, "A Variant of Langford's Problem," *The American Mathematical Monthly* (Vol. 74, May, 1967, pages 591–595).

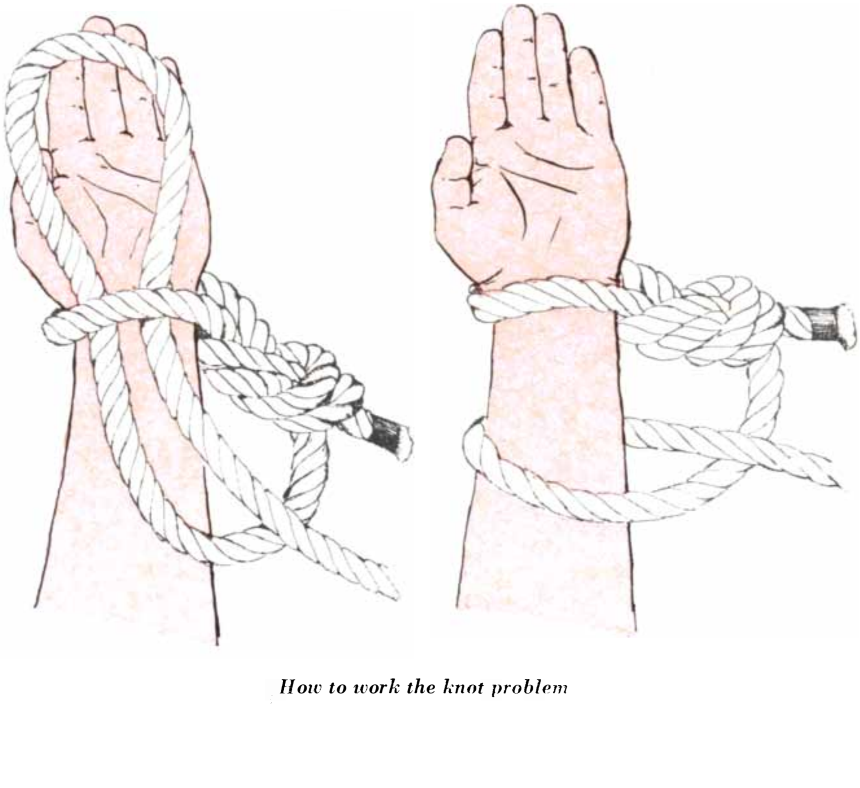
7. To solve the problem of the overlapping squares, extend two sides of the large square as shown by the dotted lines in the illustration on the preceding page. This obviously divides the small square into four congruent parts. Since the small square has an area of nine inches, the overlap (*shaded*) must have an area of 9/4, or 2¼ inches. The amusing thing about the problem is that the area of overlap is constant regardless of the large square's position as it rotates around *D*. The fact that *B* trisects *AC* is irrelevant information, designed to mislead.

8. To determine the size of the average family in Fertilia (where parents have children until they have a boy, then stop), let n be the total number of mothers over as long a period as desired. Half of these mothers will have a boy as their first child, making a total of $n/2$ children. Half of the remaining mothers, or $n/4$, will have two children, adding a total of $2n/4$ children. Then $n/8$ mothers will have three children, adding $3n/8$ children, and so on. The total number of children will be n times the series $1/2 + 2/4 + 3/8 + 4/16 + \ldots$. Since this must be divided by n to obtain the average size of a family, the n's above and below each line cancel out. The average, as n approaches infinity, is merely the sum of the infinite series.

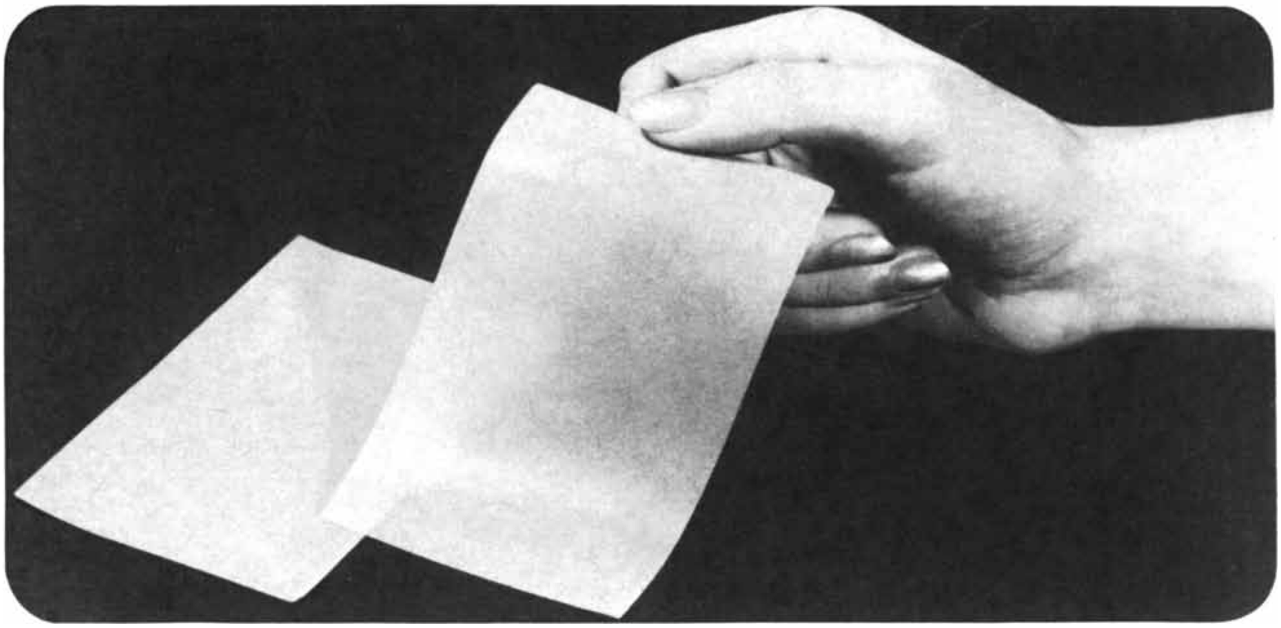
The series can be summed by a simple dodge. Halving each term gives $1/4 + 2/8 + 3/16 + \ldots$. Subtract this series from the original one and you have $1/2 + 1/4 + 1/8 + 1/16 + \ldots$, a familiar series with the sum of 1. Since this is half of the original series, the original must sum to 2. We conclude that the average family in Fertilia has—perhaps surprisingly—just two children.

9. To tie an overhand knot in the rope stretched from wrist to wrist, first push the center of the rope under the rope that circles the left wrist, as shown at the left in the illustration below. Pass the loop over the left hand, then pull it back from under the rope circling the wrist. The loop will then be on the left arm, as shown at the right in the illustration. When the loop is taken off the arm, carrying it over the left hand, it will form an overhand knot in the rope.

If the loop, after it is first pushed under the rope around the wrist, is given a half-twist to the right before it is passed over the hand, the resulting knot will be a figure eight. And if the end of the loop is pushed through a ring before the loop goes over the hand, the ring will be firmly knotted to the rope after either type of knot is formed.

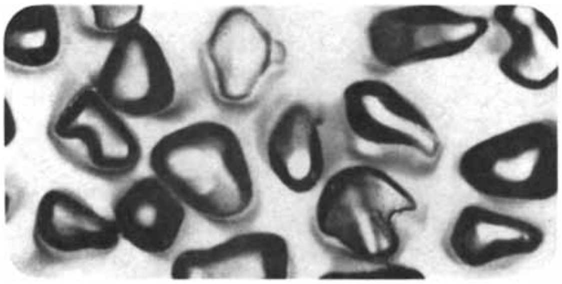


How to work the knot problem

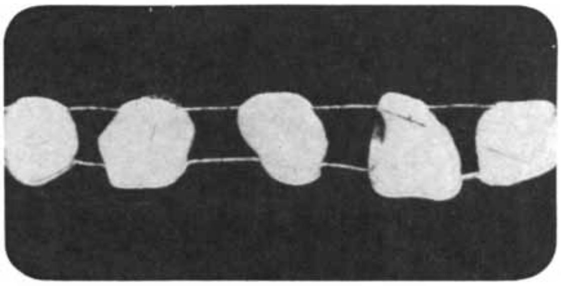


It looks like an ordinary sheet of plastic

. . . . but like this under the microscope



. . . . and like this in cross section



←40 µm→

What you see is a layer of small single crystals, with diameters in the order of tens of microns, embedded in a plastic sheet with each crystal protruding on both sides.

For a number of years now, people have been trying to make such sheets. And not without reason: they combine the high quality of single crystals with the low cost of flexible thin films. Now a suitable technique has been devised by T. S. te Velde at our research laboratories in Eindhoven, the Netherlands.

Various kinds of physical and chemical treatments, such as contacting and etching, can be carried out, since the crystals are exposed at either side of the sheet. The thin lines which you see in the right-hand photograph are evaporated metal layers which sandwich the grains and connect them in parallel.

The technique for making such layers is simple enough. A thin glue layer is applied on a substrate. The powder is then sprinkled on this layer and the grains are caught on the glue like flies on a fly paper. Surplus grains are wiped off and the layer is then dipped in a plastic which fills the interspaces and leaves the grain tops exposed. After hardening, substrate and glue are removed so that the grains are accessible on both sides of the sheet. One then has an easy-to-handle, lightweight sheet in which the grains are densely packed.

Since the starting material is a powder, the method is applicable to many different materials, including substances which are difficult to prepare as large single crystals with the desired properties.

Different types of contacts can be made on each side of the sheet, e.g. ohmic contacts on one side and rectifying ones on the other. Also, since individual crystals are isolated from each other by the plastic, series connections can be obtained between parallel groups of crystals by the proper choice of deposition patterns of the contact layers.

The method was first tried out on photoconducting cadmium sulfide. And very successfully, too. We have a firm belief in the feasibility of many other applications - one of them being for flexible solar cells with a high power/weight ratio.

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

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THE AMATEUR SCIENTIST

An Indian mound is excavated by high school archaeologists

Conducted by C. L. Stong

In 1961 members of the Northwestern California Archaeological Society surveyed an area of the San Antonio Valley in Marin County, just north of San Francisco, where they hoped to discover the remains of Indian dwellings and related artifacts. The survey was conventional in all respects but one: high school students were among those recruited to help in the work. Most archaeologists stay clear of amateurs, and for good reason. Young or old, untrained laymen tend to develop unbridled enthusiasm for the work, to strike out on their own, stumble over a site and dig up buried treasures for collections of curios. Irreplaceable information can be—and has been—so lost. If, on the other hand, one can harness the amateur's enthusiasm and direct his efforts, there may be a nice profit in terms both of recovered lore and of instruction in the potential value of undisturbed antiquities. That is what happened in Marin County.

In the course of the survey the group located a number of promising sites. One, in the form of a roughly circular mound a foot high and 100 feet in diameter located 10 miles northwest of the town of Novato, was designated Marin-374. Two test excavations were promptly made: a circular pit approximately 20 feet in diameter, where a shelter had once stood, and a rectangular pit three feet wide and six feet long just south of the circular pit. A student, Peter Moore, was made responsible for digging the rectangular pit. Although these pits produced a number of artifacts, the archaeologists decided to move on to more productive sites. By this time, however, Moore had become deeply engrossed in the work; he sought and obtained the permission of the archaeologists and the owners of the land to continue the dig. With the help of John MacBeath, a social studies teacher at the Novato Senior High School, he recruited several small teams to assist in the work and eventually helped to organize the Novato Senior High School Archaeology Club. The club, with Moore as president and in close cooperation with the archaeologists, completed a detailed analysis of Marin-374 early this year. The results of the project are reported by Terrence Jay O'Neil, who joined the club in 1966.

"I was not allowed to do any digging at Marin-374 until I had been exposed to a series of informal lectures on techni-

High school students at work at site in Marin County, Calif.

cal procedures," he writes. "In time I became responsible for mapping the site, preparing drawings of artifacts, analyzing materials and editing the final report. Approximately 40 club members had participated in the excavation by the time the work was finished.

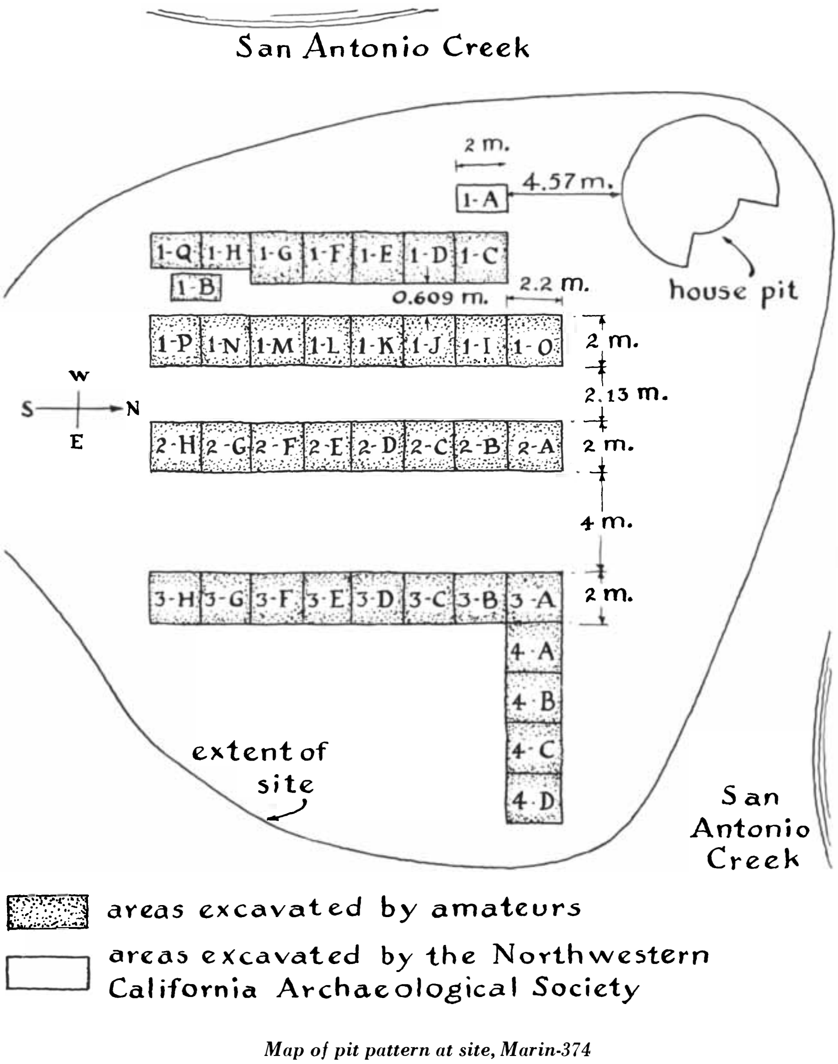
"Marin-374 is a so-called single-component site: a deposit made by people who set up a complex of dwellings, remained for a time and then disappeared. Our findings indicate that Marin-374 became a dwelling place between 2,000 and 3,000 years ago. The Indians who made and used the objects were the coastal Miwoks, who spoke the language of the Hokan group of California Indians and were descended from early settlers who established small camps in the San Francisco Bay area at least 5,000 years ago. The relative richness of the area encouraged loose tribal organization. Groups of one or two families could maintain themselves on small sites, and Marin-374 marks a site of this kind.

"The soil of the site is fine-grained, with a large amount of black organic material that contrasts with the light-colored soil nearby. In dry weather this 'midden,' when disturbed, turns into a powdery gray dust that makes excavation unpleasant in summer. The area supports foot-high field grasses, including Russian thistle, and about 25 buckeye trees, two of which stand within the boundary of the site. These trees are very old; their immediate ancestors doubtless predated historic times. San Antonio Creek, which forms the northern and western limits of Marin-374, tends to reach flood stage in early spring, but it seems not to have eroded the midden. Examination of sediments in the first four inches of the site material indicated that the topmost layer of soil had probably never been disturbed. Leaching by rain had not significantly altered the location of artifacts, as far as we could tell, nor did we find large numbers of rodent burrows—all of which led us to believe Marin-374 was an undisturbed site.

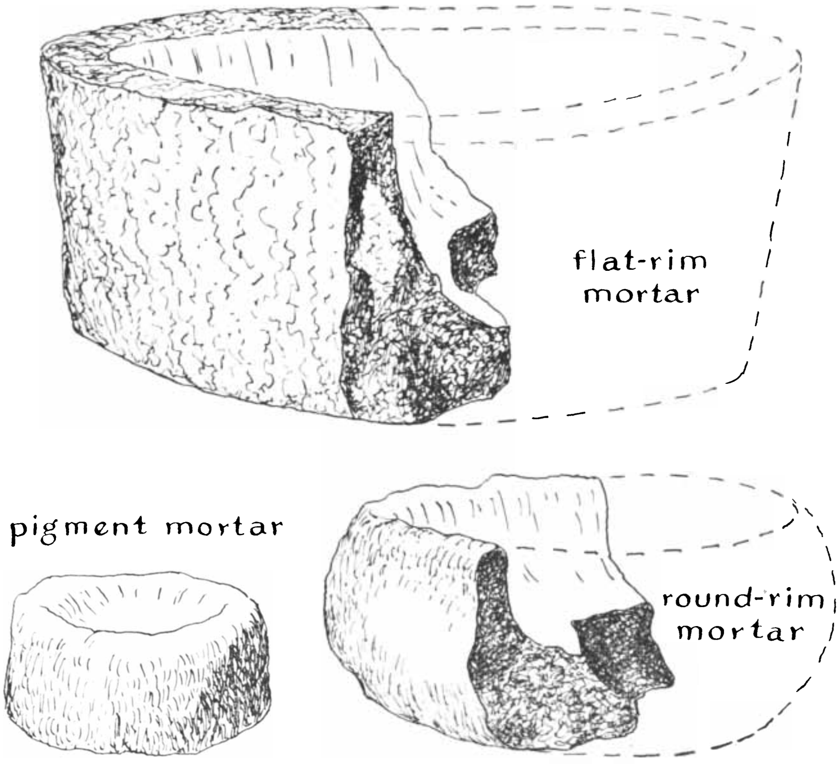
"Archaeologists have developed two approaches to excavation. In either case one begins by driving a stake that serves as a reference mark from which measurements are made, and outlining rectangular areas, usually in the pattern of a numbered grid. In the case of 'micromethodology,' the rectangular areas are then excavated one layer (about four inches thick) at a time, and the location of each artifact is recorded by exact measurements on a three-dimensional grid. In the case of 'macromethodology,' pits that measure 10 feet square are dug out in foot-thick layers and artifacts are located and recorded only by pit and layer. Scrupulous controls are maintained in all phases of excavation and record-keeping. Undisturbed soil is closely examined for any texture and discoloration that might suggest a disintegrated artifact. All soil is screened and from the screenings materials are sorted according to type (shell, bone and so on). Artifacts are inspected, described, logged and labeled for storage. In micromethodology the ratio of area processed to man-hours is low; macromethodology stresses examination of the largest possible amount of material per man-hour.

"We learned that the area of the site was scheduled to become a trailer park but that the bulldozers would not move in for some months. At the suggestion of the supervising archaeologists we laid out a grid of intermediate size that could be worked within the scheduled time. After the boundary of the site had been determined through an examination of the soil, trench lines were laid out with broad undisturbed strips between them so that representative samples of the entire site would be dug for study. In general the pits were six feet square. In one case they were arranged in the form of an **L** [*see illustration below*]. The soil was removed, in 10-inch horizontal layers, with trowels and shovels. All measurements were made in metric units to within a tolerance of 10 centimeters. Two people were assigned to each pit, one digging a shovelful at a time while the other screened and examined the material. (There are advantages to washing the soil through the screen with water, but San Antonio Creek was almost dry, and so our materials were sifted dry.) Bits of bone and other animal remains, together with fragments of rock, were collected in bags labeled according to level. Each artifact of value was labeled and listed: its pit and level number, its location and its description. Club members had been trained to recognize projectile points, scrapers, pottery and modified stone.

"Hundreds of objects were uncovered.



Map of pit pattern at site, Marin-374



Mortar and mortar fragments from the site

As we subsequently learned, the collection includes most of the types of implements that were used by the coastal Miwoks during the final stage of their cultural development. Represented in it, by class, are hunting implements, tools for preparing food and making clothes, adornments, trading goods, ceremonial items and at least one house floor.

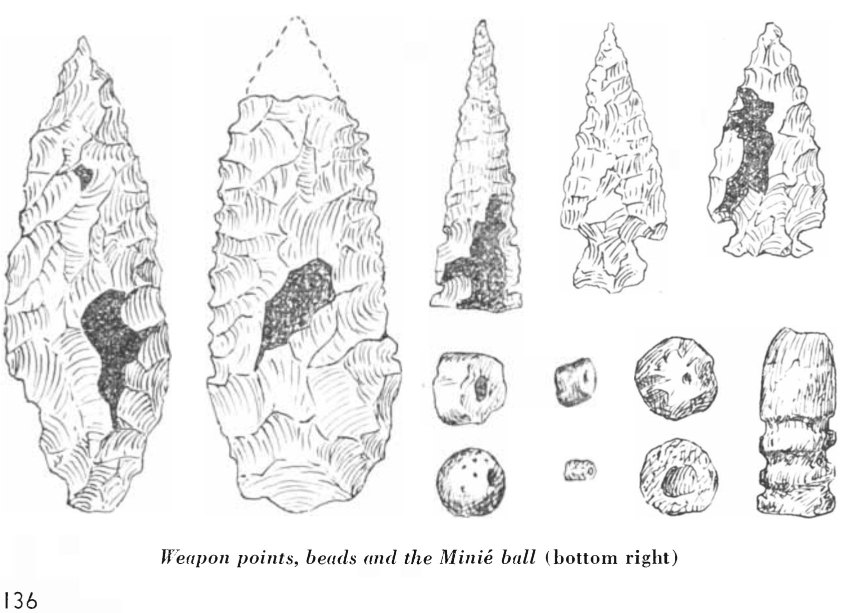
"Blades of chipped stone that were used for scraping constitute the largest single group of artifacts. A very few display remarkable craftsmanship but most are nonsymmetrical and otherwise carelessly made—generally by chipping one or more fragments from the edge of a natural fracture in obsidian, chert or other local rock. Others were improvised from broken projectile points, and one blade was made from a fragment of pottery.

"Projectile points make up the second most numerous type of artifact, and their workmanship is somewhat better than that of similar points found in other Marin County sites. Some, which appear to be unique to this site, have sawtooth edges, a notch at one corner and a concavity in the base. The points range from about two inches in length down to less than an inch. Many spearpoints were recovered, of which a few representative types are depicted in the accompanying drawing [*see bottom illustration on this page*].

"The collection includes 16 mortars and fragments of mortars, the largest of which is 32 inches in diameter. They were excavated at an average depth of about 18 inches. Two have round bottoms and round rims. Three have flat bottoms and flat rims and range in weight from 2½ to 45 pounds. Nineteen pestles were recovered, 13 of which were conical in form, five cylindrical and one globular. They were made of various native rocks, including basalt, sandstone, diorite and andesite. One bore asphaltum stains.

"A total of nine charmstones were excavated at an average depth of about 15 inches. Most were phallic types, and several had partial coatings of asphaltum. Ornamental artifacts included pennants made of shell and an earplug of steatite. Fragments of nine pipes were also found. One, of white serpentine, is excellently made and bears attractive ornamentation.

"Beads of various kinds and sizes were common. Some were made from the bones of birds; the largest was 1.5 inch in length and .4 inch in diameter. (The smallest complete bead measures a mere .06 inch in diameter—indicating the care with which the soil must be screened to ensure the recovery of interesting materials.) The collection includes various beads made from the shells of marine animals, particularly clams and olivellas; perforated disks of clamshell make up the majority. Eight stone beads made of black steatite, marl limestone and slate were found. The largest, of carved steatite, was found at a depth of 20 inches. Three beads turned up that could not have been manufactured by the limited technology of the Miwok culture. One is made of a translucent, iridescent blue glass and is oblong in shape. Another, of the same general shape but more crudely formed, is of a red glassy material that has been glazed. Both of these beads were found at a depth of eight inches. The third is of a porous, translucent yellow glass and is almost perfectly spherical; it was found at a depth of 28 inches. Obviously these beads are trade items from Spaniards or other white pioneers. Other 'foreign' objects, found near the surface, were a piece of iron in the form of a slender U, thickened in the curved



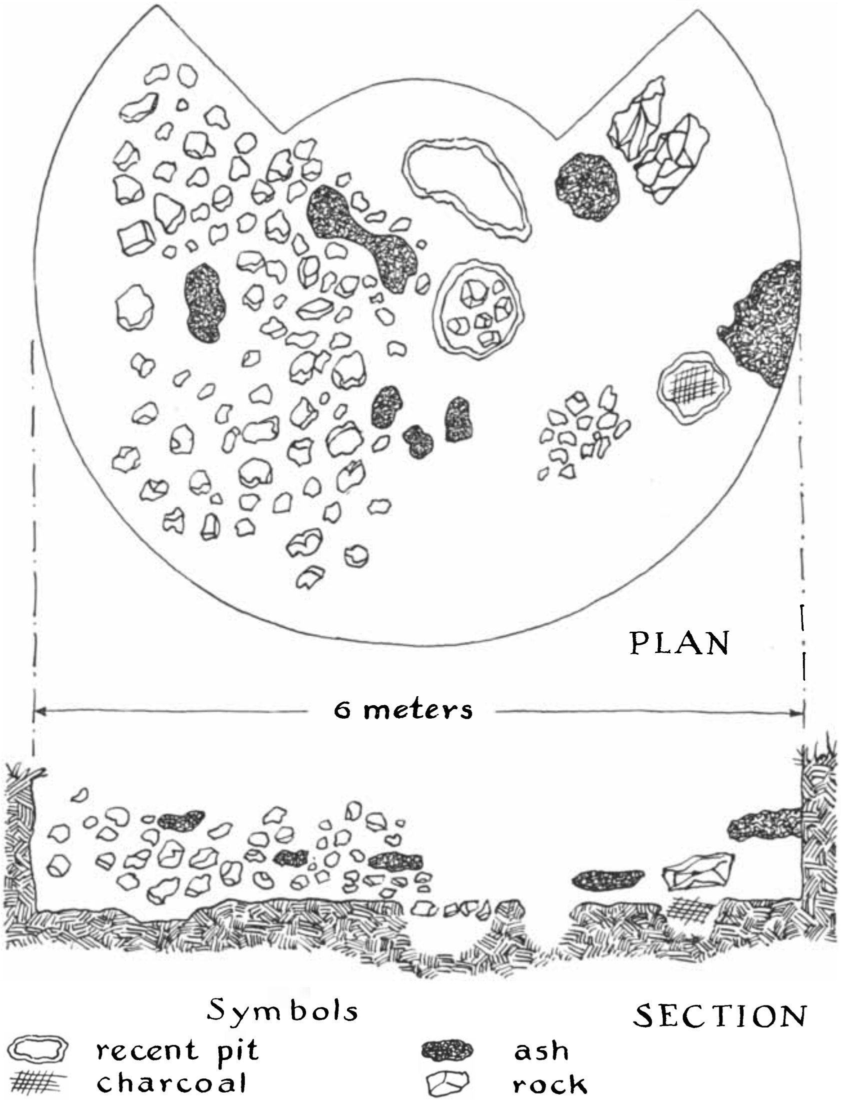
Weapon points, beads and the Minié ball **(bottom right)** portion, and two forged nails of the type commonly used during the first half of the 19th century.

"Contact between the Miwoks and the white pioneers is also indicated by a profusion of porcelain fragments in light blue, dark blue, yellow and white. Some fragments are well glazed and carry designs of thin lines in dark blue. They were found mostly on the surface and to a depth of a few inches. They have been tentatively identified as parts of 19th-century Spanish cups, bowls and plates. One white fragment had been modified by secondary chipping to serve as a scraper.

"Perhaps the most interesting evidence of foreign technology was a Minié ball found at a depth of 10 inches in pit 3-C. The somewhat dented end and the rifling marks indicate that the bullet was fired from a gun and either hit a soft, resilient surface or fell at low velocity at the end of a long flight [*see drawing at bottom right in bottom illustration on opposite page*]. We were tempted to use this artifact as a method of dating material at the 10-inch level. The Minié ball was developed by Captain Claude Étienne Minié of the French army in 1849 and quickly circled the globe. It marked a distinct advance in arms technology, since the force of the exploding charge expanded the bullet to form a gastight seal against the bore of the gun, conserving the compressed gases and increasing the bullet's muzzle velocity and killing power. Bullets of this type were in wide use in the U.S. from about 1860 to 1880. Other evidence, however, suggested a much older date for the layer in which the Minié ball was found, and it may have buried itself to this depth on impact.

"One of the most interesting artifacts turned out to be a small slab of clay that bore the impression of a woven basket. This fragment was examined by Lawrence E. Dawson at the Robert H. Lowie Museum of Anthropology of the University of California at Berkeley, who made a positive reproduction of the depressions by pressing potter's clay against the slab. The weave is much finer than the weave in similar baskets found elsewhere in California: 10 weft courses per inch and 7.6 warps per inch. In Dawson's opinion the basket was made of the split roots of a local grassy plant that resembles sedge and was so tightly woven that it must have been watertight.

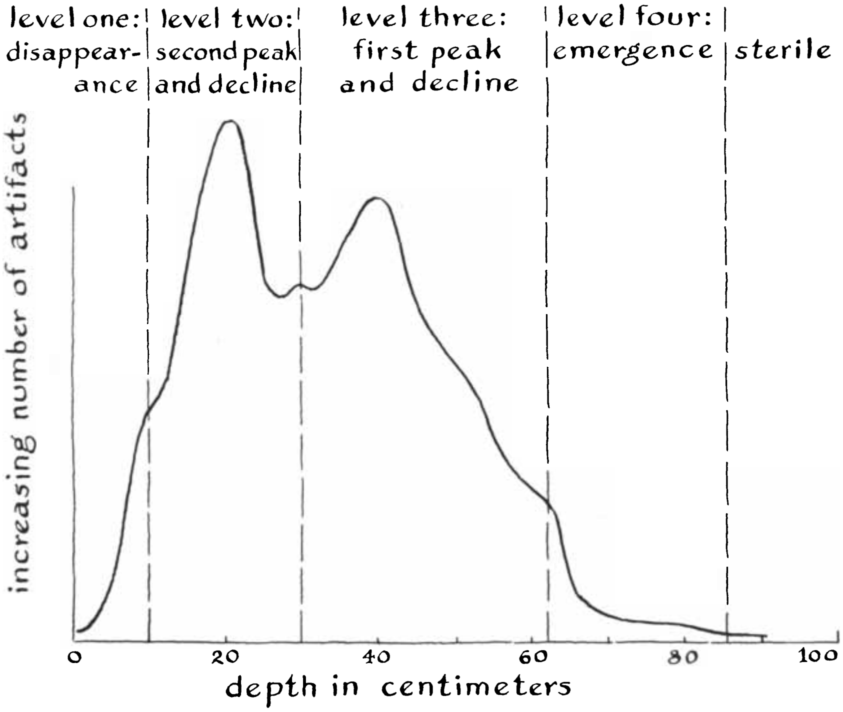
"No human burials had been made at Marin-374, although one group of bones was found that appear to be human. Four human burials were uncovered by archaeologists at a neighboring site 500 yards away.



Plan and elevation diagrams of artifacts uncovered in house pit

"The matter of dating site materials turns out to be difficult for amateurs and is relatively uncertain. It is reasonable to suppose that artifacts found at or near the surface were deposited more recently than those below. For example, one would expect to find fragments of porcelain above artifacts that were deposited before porcelain became available. On the other hand, sites can be disturbed and the materials mixed, particularly to a depth of a foot or so in small local areas. Examination might easily fail to disclose traces of a hole that was made 50 years ago by driving a stake into the ground. Yet a piece of porcelain that accidentally dropped into the hole would come to rest in a layer of materials that had accumulated centuries before porcelain could have found its way to the site. That is why sites are excavated layer by layer and a statistical evaluation is made of the contents of each layer.

"When a site contains charcoal, the possibility exists of dating the layer by the carbon-14 technique [see "The Amateur Scientist," February, 1957]. Our site contained no usable charcoal, however. Only one modern technique of dating was available to us: the hydration method, which is based on the slow corrosion of glassy materials by water. Obsidian and other glassy materials that are moist tend to corrode very slowly through the centuries at a constant rate. Water that is naturally present in the soil diffuses into the noncrystalline structure of the glass and leaches out soda, lime and other substances, thus creating a surface skeleton of silicon. The action is retarded during dry weather. The result of prolonged exposure to varying wet and dry seasons is the growth inward of alternating dark (unleached) and clear



Graph showing distribution of artifacts by depth

(leached) bands roughly analogous to the annual growth rings in trees. The partial reflection of light by the layers sets up optical interference between reflected light waves with the result that the corrosion appears in the iridescent colors observed occasionally in old glass [see "Ancient Glass," by Robert H. Brill; SCIENTIFIC AMERICAN, November, 1963]. The fragile layers tend to flake away when the glass is touched, particularly in man-made glass, and so artifacts to be dated by the hydration method must be handled gently. Technicians select specimens that show little wear and remove slices frcm facets that appear to be fashioned by man—not from surfaces of natural origin. The slices are ground to thin sections and treated chemically to emphasize the bands. The bands, which vary in thickness from about 20 to 120 millionths of an inch, are then examined under a microscope.

"Amateurs who are skilled in lapidary techniques could doubtless master the hydration method of dating, but we did not attempt it. Instead we submitted 18 specimens of worked obsidian to Harvey Crew of the University of California at Davis for analysis. Two of the specimens were unsuitable for analysis; the remainder indicated ages ranging from 680 to 1,800 years, with the exception of one that indicated 2,900 years.

"A lot of work went into the excavation of Marin-374. At the conclusion of the dig we spent three months compiling data and writing a report that has been distributed to interested archaeologists. Some of the recovered artifacts are now in storage. Others are on display at the Boyd Natural History Museum in San Rafael, Calif., or in the files of the University of California at Berkeley and San Francisco State College, along with copies of our report. When a museum now being considered by the Novato Parks and Recreation Department is completed, most if not all of the items will be on display. Copies of our notes are available on request. We have been invited by David Fredrickson of the department of anthropology at Sonoma State College to participate in the excavation of Marin-27 in Tiburon, Calif., and are now developing plans for a high school class in field methods.

"About 60 percent of Marin-374 was left undisturbed; doubtless it contains more material than we removed. Soon the site will be obliterated by earth-moving machinery, as was a neighboring site, Marin-196. We have recently participated with local archaeologists in a successful campaign for an ordinance forbidding the destruction of sites in Marin County by commercial agencies until a representative sample of artifacts has been unearthed.

"The dig at Marin-374 was a fascinating (if sometimes exhausting) experience, and our club members enjoyed it thoroughly. We feel that our work helped, if only a little, to reconstruct the story of how the Miwok Indians lived during their last 1,500 to 2,000 years.

"There are records of contacts between these Indians and Spanish settlers, but no substantial intermarriage with the Spaniards took place and the line seems to have died out. We have heard, however, that one mixed-blood coastal Miwok still lives in Marin County. We are trying to locate him—or her."

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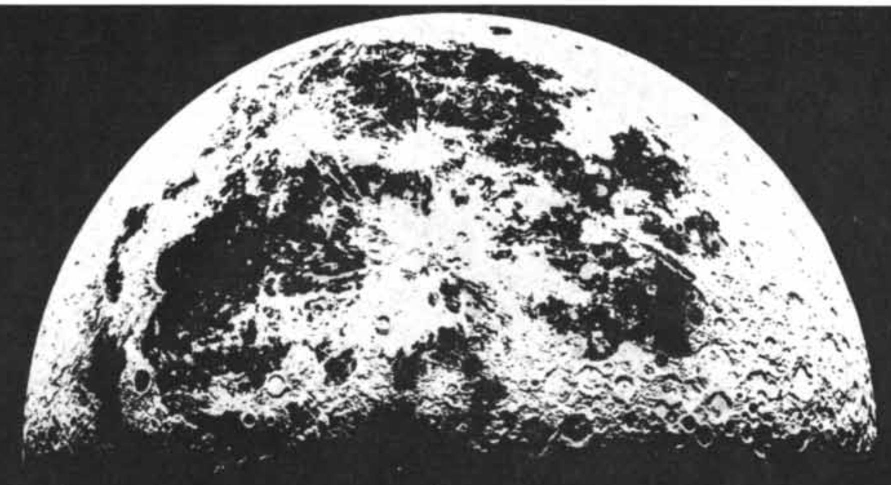

The same digital computer space photo process that sharpened the pictures of the Moon and Mars now clarifies the map of an Earth Man skull.

Jet Propulsion Laboratory originally developed this photo enhancement process to remove distortions in photographs of the Moon taken by Ranger and Surveyor spacecraft, and of Mars by Mariner IV. Then somebody went one step beyond (no pun intended) and said, "If it works so well on space-photos, why not try it on x-rays?" Well, this is exactly what's happened. JPL has analyzed x-rays from some of the nation's leading medical schools and clinics. X-rays of the brain, heart and lung areas, x-rays of the chest and skull, photographs of the retina have all been uniquely "computerized".

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JPL's Digital Computer Processing of x-rays has recently been selected as one of the "100 most significant new technical products of the year" in the fifth annual I-R 100 Competition. At JPL... the sky's not the limit. To find out more about this project and other present and future JPL projects, write to Mr. Wallace Peterson, Supervisor, Employment.

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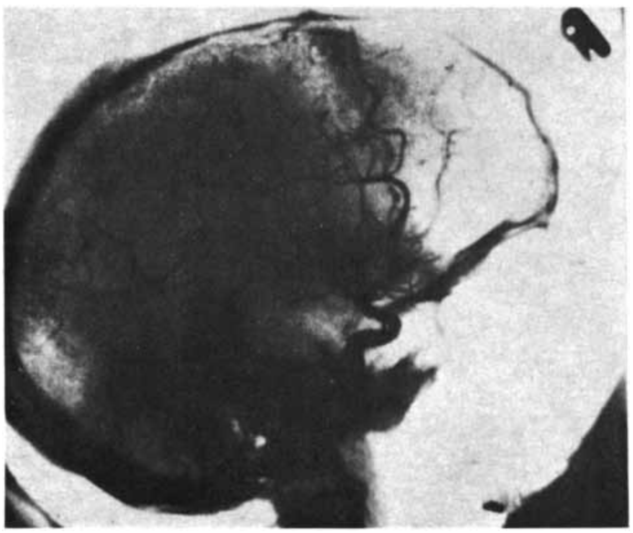
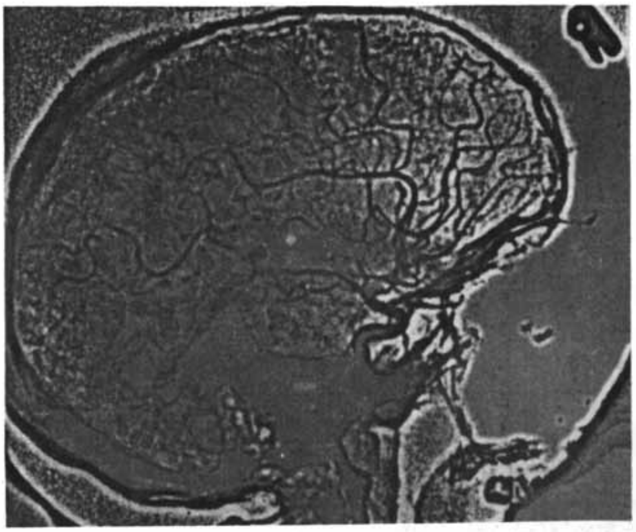
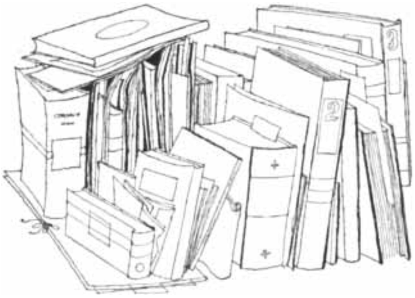
See for yourself. X-ray at left is unprocessed. JPL's computer enhancement process brings out blood vessels "lost" in the highly exposed frontal portion of the skull.







BOOKS

Books about science for younger readers

by Philip and Phylis Morrison

In the tradition established by James R. Newman, we once again present a Christmas collection of reviews of children's books on scientific subjects. If there is any generalization to be made about the current crop, it is that this year we found more good books than we did in 1966 but fewer memorable ones.

Astronomy

OBSERVING EARTH SATELLITES, by Desmond King-Hele. St. Martin's Press, Inc. ($7). King-Hele is a British expert in the use of artificial satellites to probe the high atmosphere and the gravitational field of the earth. But he is no armchair theorist. Rather, stopwatch in overcoat pocket and star atlas under his arm, he watches the sky with his own eyes and binoculars "from a deck chair set at the lowest notch." He has as a spare-time observer watched more than 200 satellites make an average of six or eight transits each. In this knowing book he not only presents a how-to-do-it in all detail for a new and exciting form of stargazing but also illuminates the whole engineering and scientific surround, from the worldwide networks tracking with giant cameras and radio beams to those fortunate physical properties of our earth that make satellite-viewing accessible to amateurs. Any young people and their families who have some clear, dark sky at their disposal will find this work an absorbing guide, whether to a casual look now and then at a space balloon such as *Echo* or to a serious and enduring pastime of real scientific value. To use the book you need to understand tables and graphs but not how to manipulate formulas. A list of no fewer than 30 choice visible satellites closes the book. Personal authority shines through each page of the light, literate and allusive text.

RED GIANTS AND WHITE DWARFS: THE EVOLUTION OF STARS, PLANETS AND LIFE, by Robert Jastrow. Harper & Row, Publishers ($5.95). A good many volumes exist that survey in simple language the whole sweep of our present view of how things came to be as they are. This is an admirable member of the genre. It is free of mathematical formulas, not even using the power-of-10 notation. The language is smooth and engaging, the tone humane and lighthearted, and the ideas flow out of the thought of one understanding man who seeks to make them real. The book is handsomely illustrated with photographs. The pictures of scientists of the day are engaging, showing them mainly in context and not as studio subjects. The story is not so philosophically put as it could be, but it is always viewed for its meaning as a whole.

Our view of the world is not so engaging as De Fontenelle's, quoted in the book: "I can tell from here . . . what the inhabitants of Venus are like; they resemble the Moors of Granada; a small black people, burned by the sun, full of wit and fire, always in love, . . . arranging . . . tournaments every day." But given our times the wit and fire of our cosmological thought are well set out by Jastrow in a book that almost any teenage reader can enjoy and profit from.

THE STAR LOVERS, by Robert S. Richardson. The Macmillan Company ($7.50). Sixteen biographies of astronomers, including the great pioneers Brahe, Newton and Halley, the less well-known Horrocks and Roemer, 19th-century heroes such as Encke, Janssen and Hall, and two personal acquaintances of the author, Seth Nicholson and Walter Baade. Baade was probably the leading optical astronomer of this century. The great wartime campaign of Baade at the 100-inch reflector on Mount Wilson, which first succeeded in resolving stars in the central portion of the Andromeda nebula and led to the recognition of stellar populations, is described in detail. Success depended on the wartime blackout of the Los Angeles city lights and on Baade's German background, which kept him out of the very war work that called away most of his rivals for telescope time. These are lively and personal biographies, but the unflagging Indiana humor with which they are told may not suit everyone.

THE LOOK-IT-UP BOOK OF STARS AND PLANETS, by Patricia Lauber. Illustrated by John Polgreen. Random House, Inc. ($3.95). Simply and honestly written, here are a hundred pages of alphabetized entries, *asteroids* and *atoms* to *Venus* and *zodiac,* that a child can understand and enjoy. The brief text displays unfailing good taste about where to start and how far to go. The reproduction is excellent at the price, and many of the famous Mount Wilson and Palomar color photographs are here. The schematic drawings are done in a free and colorful calligraphic style.

THE STARS: A NEW WAY TO SEE THEM, by H. A. Rey. Houghton Mifflin Company ($6). A new edition, with up-to-date planetary tables and glossary, of this extraordinarily helpful guide to the constellations.

Physics

BASEBALL-ISTICS (THE BASIC PHYSICS OF BASEBALL), by Robert Froman. Illustrated by Sam Salant. G. P. Putnam's Sons ($3.49). The slightly creaky framework of an imaginary World Series game—with international players and interplanetary ringers—of the year 2000 carries a well-balanced load of physics. Each half-inning makes some point, from speed and acceleration in throws and slides to the momentum balance between bat and ball in a bunt. The wobble of a spinless knuckle ball and the fall of a base runner who has lost a little of the needed friction are about as deep as the treatment goes. It touches quantitative dynamics at some points, using poundals for force units. Altogether it is an attractive work, if indeed readers beyond the fifth grade are found who will

enjoy this horsehide-coated and good-humored lesson.

FLOATING AND SINKING, by Franklyn M. Branley. Illustrated by Robert Galster. Thomas Y. Crowell Company ($3.25). ADVENTURES WITH A STRAW, by Harry Milgrom. Illustrated by Leonard Kessler. E. P. Dutton & Co., Inc. ($2.72). ADVENTURES WITH A PLASTIC BAG, by Harry Milgrom. Illustrated by George Wilde. E. P. Dutton & Co., Inc. ($2.72). Three very simple experiment manuals aimed at five- to nine-year-olds, with experiments they can really carry out with familiar household things. The first has a wider use of analogy and comment. The second and third texts are mainly, but not wholly, in question form. It is surprising how wide a range of topics can be approached with a plastic bag or a soda straw. A cylinder is defined quite kinematically as an object that rolls one way and slides another way. "You know that a bottle of air floats. Would a bottle of water float? You can find out."

WHAT DOES THE TIDE DO?, by Jean Kinney. Illustrated by Cle Kinney. Young Scott Books ($3.95). Young Damon lies prone on the dock, and below him he sees the wet sand with a scuttling crab but no water for fish. All day he spends as he has determined to do, watching the sea flood in, first green and then blue, bringing with it the great fishes of the deep, before it ebbs once again at the end of his long watch. With colorful drawings and an inviting story to read or to listen to, this is a first-rate introduction to science, to watching and thinking about how the world works.

Geology

ROCKS AND RILLS: A LOOK AT GEOLOGY, by A. Harris Stone and Dale Ingmanson. Illustrated by Peter P. Plasencia. Prentice-Hall, Inc. ($3.75). Once again Professor Stone and his co-workers have created a brief and splendid book, mainly out of artful questions about simple things you can do in the kitchen. The book is aimed at boys and girls of 10 and up; there are many reluctant students of required college geology to whom it would also bring meaning and coherence. Philosophers may find a tendency, like that of Einstein himself, toward opportunism: "The scientist has no rules to direct his studies. He may do whatever he thinks will help him find an answer. ... Find one answer at a time and don't forget to ask questions."

Geology is not usually held to be an experimental science. This wrong-minded tradition does not daunt these authors. They produce a variety of workable experiments—relevant not merely by analogy but by implicit scaling in space, time and the properties of materials—that elucidate the processes of physical geology. Let water drip out of holes in a paper cup full of sand. Freeze a plastic bottle of water in the refrigerator. Use a fan blast, a garden hose and an ice cube to move some pebbles and sand. Stir a mix of gravel, sand and chalk and let them settle in a glass of water. Each one is a process also seen on a geological scale, the last leading to graded bedding. True, outdoor geology is missing still; the landscape forms are only mentioned in this introduction and no numbers occur. Add those and a beginning geology would be here.

GEMS, MINERALS, CRYSTALS AND ORES: THE COLLECTOR'S ENCYCLOPEDIA, by Richard M. Pearl. Golden Press, Inc. ($2.95). Where mineral names come from, how to set up a collection, a few pages on a gem-cutting shop, a glossary of terms of the art, keys to identification of minerals and 64 pages of handsome color photographs of mineral specimens comprise this inexpensive book, a kind of extended technical dictionary that is a real bargain for the interested.

WONDERS OF SAND, by Christie McFall. Dodd, Mead & Company, Inc. ($3). Magnified sand grains have the beauty of gems, and their nature is easy to read: angular, polished or frosted. From this grain-by-grain start the book goes on to tell very simply of beaches, dunes and deserts, of how they move and shift, of how men have tried to manage the sands and of how sand finds a use. The prose is pretty flat, but the book is worthwhile in spite of the style for the strength and clarity of the ideas and for the visual materials it presents.

Mathematics

BASIC: AN INTRODUCTION TO COMPUTER PROGRAMMING USING THE BASIC LANGUAGE, by William F. Sharpe. The Free Press ($3.95). The obedient and unimaginative contemporary computer is always instructed in detail how to perform its tasks. Such instructions are nowadays written out in a language men can easily learn and understand; the machine has a translation device to convert the simple vocabulary and logical grammar into the long strings of digits that are its own language. The first simple program language of real power is called BASIC. With the initial hour of classroom instruction, or the first chapter of this phrase book, a student can begin commanding the machine. In five or 10 hours he can learn to instruct the djinn with a flair.

BASIC is the outgrowth of the experience at Dartmouth College, which has led most undergraduates there (not merely the science-directed ones) to use the time-shared computer terminals located all over the campus. Many computers now know BASIC, and the book tells how one can arrange BASIC lessons for any reasonably talented computer.

With this book anyone can see in detail how to command a computer to produce payrolls, grade papers, analyze questionnaires or work out a wide range of problems. It is of course best to have a real BASIC-speaking computer to talk to, but it is not necessary; one can learn to speak French without a French partner, although it is surely less fun.

This is a serious start at computation, accessible to just about every interested reader past the sixth grade. In Hanover, where there are lively keyboards in many unlocked rooms, lots of grade school youngsters use BASIC freely.

MATHEMATICS ON VACATION, by Joseph S. Madachy. Charles Scribner's Sons ($6.95). Dozens of worthwhile volumes of mathematical recreations are in print in the U.S. Here is a fine new member of the class. It is well made, clearly illustrated and furnished with an excellent glossary and bibliography. It contains both old favorites (flexagons and magic squares, for example, in wide variety) and new departures such as three-dimensional "flexahedrons" and antimagic squares (in which all the rows and columns add to different numbers). The author is the founder and editor of *Recreational Mathematics Magazine*, discontinued a few years ago but now reborn, which is the source of much of the new material. Fans will find this volume indispensable; casual readers will find it an attractive nuisance. It is cheering to realize that someone at the Rand Corporation computed (after hours, one imagines) the first 1,200 digits of the number 9^{99}. (The first 10 digits are cited in the book, and the last 10 too.)

PROBABILITY: THE SCIENCE OF CHANCE, by Arthur G. Razzell and K. G. O. Watts. Illustrated by Ellen Raskin. Doubleday & Company, Inc. ($2.50). Two London educators address this likable, slender book to fifth- and sixth-graders. They talk about the nature of prediction, about making histograms, in

a general way about distributions and about using sampling to count the uncountable. Their proposals for statistical activities by children are pleasant and workable. Purists would criticize their implied treatment of the law of large numbers, which they must handle elliptically because limits and ratios are properly not explicit in the text. The strong and colorful drawings take the book well out of the common run of textbooks.

THE GRAPHIC WORK OF M. C. ESCHER, by M. C. Escher. Meredith Press ($7.95). The prints of this modern Dutch master are well known to readers of SCIENTIFIC AMERICAN. Their technical brilliance and wide-ranging imagery would in any event predispose viewers of scientific tastes toward appreciating them, but as most of the world now knows, Escher has understood more deeply than any artist today the mathematical structure of space, of perception and of pattern. In this brand-new edition the artist gives us quite a few pages never before published in addition to the old familiars. There are four prints in color, including one reproduced on the jacket that shows us a polytypic species of lizard that seems to nest in the pyramids of a dodecahedron, one lizard of a distinct color to each point. Three spheres on the table, one like crystal, one a mirror and one of ivory, draw in the viewer as they absorbed the artist. The regular divisions of the plane are here, of course, 15 in black and white. Anyone who likes to use his eyes well, whether in the artist's domain or the scientist's, will be gripped by Escher. This work is at once a challenge and a charm for children, who will work out for themselves step by step new points of understanding.

Animals and Plants

SO EXCELLENT A FISHE: A NATURAL HISTORY OF SEA TURTLES, by Archie Carr. The Natural History Press ($5.95). Eggs, soup for aldermen made of the gelatin of the stomach plate, tortoiseshell for eyeglasses—the sea turtle is prey to many men. This unusual pelagic reptile has been the concern of the author for more than a decade. In this discursive and marvelously diverse book he tells his own story and the turtle's. Some species of turtle are mortally threatened, and he has tried hard to beat back the threat in the Caribbean. He tells of the nesting of packs of turtles on the Mexican coast, a curious and fascinating tale. Most curious of all is turtle navigation; one species finds its way across half of the South Atlantic to breed on little Ascension Island, only five miles across. Carr and his colleagues have done a lot with turtles to work out that island-finding; they have not got far with the problem. Turtles with filtering spectacles, turtles with antenna rods, turtles with attached four-foot yellow balloons floating high above them in the air are some of the signs one might have seen of these studies. If that skill is not based on smell, on magnetic fields, on inertial guidance or on the earth's rotation, then maybe it is done by stargazing. There are not yet many data for a judgment. More will come once Carr begins to track the turtles by radio signals picked up in a satellite in orbit overhead. Maybe. The subject is still mainly a program. High school readers will enjoy this rather musing book.

THE LIFE OF THE KANGAROO, by Stanley and Kay Breeden. Taplinger Publishing Co., Inc. ($4.95). The mob of gray kangaroos and their little joeys that live on a coastal island about 20 miles north of Brisbane in Australia are the topic of this photographic essay. The pictures are splendid and numerous, the text is clear, the observations are made with insight and affection. On this wild island the kangaroos were without fear: "they let people approach within feet." The result shows here; this is a first-rate example of modern natural history, looking at one endearing species in some depth but wholly without technical barriers to any reader.

THE WORLD OF THE POLAR BEAR, by Richard Perry. University of Washington Press ($5.95). This is an expert treatment of the largest of living land carnivores, based on library research rather than on direct experience and correspondingly broader of view in space and time than the more intimate book listed above. It is a detailed text telling of the life of the bear on the drifting pack ice, the long and fascinating history of explorers and Eskimo hunters and watchers as they came to know the great beast. Alaskan safari hunts in light planes and zoo keepers anxious for more white bears are dread enemies to the Nanook, and the species, now numbering 10,000 around the roof of the world, is in real danger. A solid and meaty book for interested readers of 15 and up.

ANTS FROM CLOSE UP, by L. Hugh Newman. Photographs by Stephen Dalton and others. Thomas Y. Crowell Company ($6.95). The ants have often been the subject of reflective naturalists, and their varied and complex behavior deserves it all. Here is an up-to-date look at ants done unsentimentally by an experienced British writer on insect life, not at all technical but quite detailed. The photographs are remarkable, about 70 of them in black and white, mostly showing the ants "close up" and big enough to see plainly. The stereotyped behavior of the ants is marvelous, but it has its evident limitations and imposes much lost effort and confusion in changing situations. The mites of ants are common and important; one species of ant mite feeds on a more harmful mite species, making a very good start toward Swift's aphorism on fleas.

THE FIRST BOOK OF FRUITS, by Barbara L. Beck. Pictures by Page Cary. Franklin Watts, Inc. ($2.65). The fruits of this handbook are not only the technical fruits of the botanist but also those that are good to eat, from apple, peach, mulberry and chestnut to breadfruit and cherimoya. The text is arranged systematically and gives a little botany, a little geography and a little history for each fruit. The pictures (in black and white) are handsome and full of meaning. The trail from commonplace experience to the far away and long ago is well marked here, and it becomes a lasting piece of proto-science for children who can read.

MILKWEED, by Millicent E. Selsam. Photographs by Jerome Wexler. William Morrow & Company Inc. ($3.95). For readers up to the fourth or fifth grade, each page has a few lines of text in big type and a handsome photograph, in all half a dozen in color and some 30 in black and white. Most of the photographs are striking views at tenfold magnification of parts of the milkweed flower or seedpod or of the insects it attracts. The book is one gate into a new world—the world of the small and its meaning.

THE TOAD HUNT, by Janet Chenery. Illustrations by Ben Shecter. Harper & Row, Publishers ($1.95). Two small boys who look quite content with the world try to find a frog—or is it a toad?—that has startled them. They find out many things, even that there are different names for fellows with smooth skin and lumpy. Beginning readers will enjoy the lively story.

CHARLOTTE'S WEB, by E. B. White. Illustrations by Garth Williams. Dell Publishing Co., Inc. (75 cents). A bargain paperback edition of a book about a spider that was a true friend and a good writer.

Biology

Blood, by Leo Vroman. The Natural History Press ($4.95). "I am a nature lover; but maybe for lack of larger scenery, I have learned to enjoy the table-top-sized scenery inside me," begins Dr. Vroman. Personal, candid, self-revealing, self-illustrated with line drawings that are usually rather droll, brilliantly clear on more than one major topic, this small book is a find. It treats of clotting and proteins, mutation and cells. It begins with as open an account of the life of a graduate student as one can easily find; it sums up clinical research and the patients whose travail lies behind it; it sensibly connects the realm of laboratory hardware with that of molecular structure; it handles number and magnitude with a deft mix of sharpness and approximation. One pays a small price: Vroman is so eloquent and so engaged a writer that he sometimes produces metaphor too strong for the occasion, more crimson than blood. That price is worth paying. His science draws the reader in and his attitude wins him. Listen to his comment on mutation: "That is what I call amplification, and frankly, meeting it in a patient has become too big an event for me, too big and irreversible an injustice to face helplessly every day. I am not a doctor, I am a Ph.D., and all I want to concentrate on is facts, not reality. And indirectly, I may help a bit."

The Life of Prairies and Plains, by Durward L. Allen. McGraw-Hill Book Company ($4.95). From Kankakee to Fort Collins and from the Pecos north to Saskatchewan there was once a sea of grass. Here is the story of that sea, a vast community of life from stalking Pawnee hunters up to the high-flying curlew and down to the stalks of blue grama, viewed as it might have been before Columbus came. The text, clear and biologically knowing, does not omit the history of the land. We read of the depths of the past when the plains were home to a fauna as varied as that of modern Africa, and we learn as well of the time when the Plains Indians came to know them and to live by the horseman's skill. The book is explicitly an elementary ecology, tracing the energy fed into this "empire of the sun" up from the first user, the grass itself, to man at the uncertain pinnacle of the pyramid. It stops short of any account of man's crops; the buffalo plains, in all seasons and all lights, are its center. This is the true fabric of the American pastoral, here simply and factually woven out of science and the work of painter and traveler. The photography is rich and varied; dark herds of bison dot the golden prairie in the July sun, and the booming sage grouse in fall is no more striking than the rolling land locked in the snow.

This book is perhaps the freshest of a continuing series on cave and forest, ocean and marsh. But all of them produce a very favorable impression; they have individual authors with names and spirit, ideas and an aim. There is an excellent index, a helpful introduction to the collecting and identifying of grasses and a listing of grassland areas held by the Department of the Interior. The National Bison Range north of Missoula, Mont., appears as our version of the Nairobi game park.

The Mysterious Grain, by Mary Elting and Michael Folsom. Illustrated by Frank Cieciorka. M. Evans and Company, Inc. ($4.50). The most important crop in this country is corn. It is an American invention, developed 6,000 or 8,000 years ago by the ingenious people of the Tehuacán valley in Mexico. Darwin himself was puzzled by corn; although it showed much variation, it could not maintain itself by scattering seed and must have evolved under man's care. This book, written for readers in junior high school and up, tells how men came lately to understand how corn arose. It is a story of conjecture, of analogy, of plant breeding, of old pottery and much patient digging. It is full of argument and debate; there were many false starts. Tiny cobs have been uncovered deep in the caves of Tehuacán from a layer so old that farming was unknown. A plant like that old wild corn has been reborn by selection and grows each year in a test garden near Cambridge, Mass. The drawings are lifelike and carry much of the persuasion of the book.

Water Animals for Your Microscope, by Edward Lindemann. Illustrated by Christine Sapieha. Crowell-Collier Press ($4.50). Young experimenters who have learned how to use a pretty good microscope and are looking for new views will find this an excellent guide to a whole microworld of the life of fresh water and ocean, with many experiments on the behavior of the animals they can grow and watch.

Discovering Insects, by Glenn O. Blough. Pictures by Jeanne Bendick. McGraw-Hill Book Company ($3.50).

Deftly written, with informal crayon and pencil sketches, these pages tell a story for young readers. The story is about a boy called George who found out a lot about the insect life in his own yard, and step by step you are told on the simplest level about insects and led on to find out more for yourself. "If you don't have a yard, look in the park, . . . or even in a window box. . . . You'll make more discoveries if you use a magnifying glass." The last words of this engaging book are on a scroll under a picture of George's hornet's nest: "George's Mother is a good, patient lady."

ANATOMY AND PHYSIOLOGY FOR CHILDREN EXPLAINED THROUGH THE DISSECTION OF A CHICKEN, by Jean M. Ashton. Dover Publications, Inc. ($1.50). Exactly how to dissect a New York dressed chicken, cold but not frozen, is set out here in text and drawings aimed at third-grade classrooms and up. You can cook and eat the subject afterward! There is a second part, not including dissection, making comparisons with the human body. This is a tour de force of teaching; it ought to work splendidly as well for individual children with a genuine interest in the task.

POND LIFE: A GUIDE TO COMMON PLANTS AND ANIMALS OF NORTH AMERICAN PONDS AND LAKES, by George K. Reid. Golden Press, Inc. ($1). The physics, the origins and the dwellers of ponds and lakes, from blue-green algae to the great blue heron, set out in a pocket-sized, simple text and 500 color drawings. This is one more bargain book in this familiar series, suitable for anyone who messes about in fresh water.

ENJOYING BIRDS AROUND NEW YORK CITY, by Robert S. Arbib, Jr., Olin S. Pettingill, Jr., and Sally Hoyt Spofford. Houghton Mifflin Company ($4.50). This is a book that admirably meets its one clear claim. It maps out and describes across 60 pages the exact places where birds can be found within the region bounded by Dutchess County, Montauk and Staten Island, and what birds are best sought out in each place. It tells just how to get there by car or public transportation. Then it tells when to try, both in a general calendar and week by week for each species. A simple text account and a neat pen drawing is given for 100 of the most probable finds.

"IN WILDNESS IS THE PRESERVATION OF THE WORLD," by Eliot Porter. Sierra Club/Ballantine Books, Inc. ($3.95). A small-page paperbound version of the well-known collection of Porter's sensitive photographs in color to the outdoor texts of Henry David Thoreau. Beautifully made at a low price.

Man in the Past

GILGAMESH: MAN'S FIRST STORY, written and illustrated by Bernarda Bryson. Holt, Rinehart and Winston, Inc. ($4.95). HE WHO SAW EVERYTHING: THE EPIC OF GILGAMESH, retold by Anita Feagles. Illustrated by Xavier Gonzalez. William R. Scott, Inc. ($4.50). Before any word was written the epic of Gilgamesh of Uruk was shown in pictures carved on cylinder seals. Here are two splendid versions of that ancient story, told for reading by or to children "of all ages." The first book, which has the fuller text, is illustrated with glowing colored wash drawings evocative of particular artifacts of the ancient kingdoms. Nearly every page of the second book, which is shorter and more lyrical in language, has a photograph of the wonderful white-paper sculpture made by Gonzalez.

Gilgamesh once slept for several days when he should have been awake. To prove this to him his hostess baked a loaf of bread each day. "At the end of the seventh day the first loaf was hard, the second was like leather, the third was soggy, the fourth was moldy, the fifth was beginning to mold, the sixth was fresh and the seventh was still in the oven." A story like that is no worse for 5,000 years of aging. These are two beautiful and fascinating books for both children and their parents.

THE ALCHEMISTS: FATHERS OF PRACTICAL CHEMISTRY, by Richard Cummings. Illustrated by Yukio Tashiro. David McKay Company, Inc. ($3.50). In the past 10 years the historians E. J. Holmyard, John Read and F. Sherwood Taylor have each told the tale of alchemy freshly and with a profound and scholarly appreciation. This modest book, acknowledging the work of those very authors, is a simple and attractive retelling done in the form of brief biographies of nine famous alchemists, from Bolos Democritos of Alexandria to the last practitioner, poor James Price, who died in 1785 by his own hand in the presence of the expert committee of the Royal Society that had come to watch him "try the projection." The Chinese and Arab traditions are properly represented, as well as the wonderful story of Alexander Seton, who left behind in a dozen cities of central Europe fine gold he had made from lead, sulfur and a little of his secret yellow powder. Seton died, without revealing his methods, of torture ordered by Christian II of Saxony, but he first bestowed some powder on a disciple. He too succeeded in the art of transmutation, until in turn *his* patron, the emperor Rudolf, caught him faking. Perhaps Seton's powder had run out. Cummings, citing Chaucer's false Canon who hired the yeoman of Canterbury, ingeniously and convincingly gives his version of Seton's real art. Alembics, seals and symbols, above all the great worm Ouroboros, embellish and enlarge the text.

INDIAN MUSIC MAKERS, written and illustrated by Robert Hofsinde (Gray-Wolf). William Morrow & Company Inc. ($2.95). An old Minnesota trapper, Robert Hofsinde was adopted into the Chippewa long ago. He has become an authority on Indian lore, with a dozen small, topical books to his name. Here he describes clearly in words and in sharply detailed drawings how tom-toms (one-headed drums), drums, rattles and flutes were made by Indians from Puget Sound to Massachusetts Bay. It would take a great deal of skill to make the instruments drawn here, but the sense of just how they were built is strong and authentic.

THE MORNING OF MANKIND: PREHISTORIC MAN IN EUROPE, by Robert Silverberg. New York Graphic Society Ltd. ($4.95). The little girl looked up at the low cave ceiling that her father, preoccupied with digging, had never seen. So were the bison paintings of Altamira discovered. Beginning with this famous tale, the experienced author relates, mainly in a sort of historical narrative, the growth of our knowledge about early man in Europe, from Chellean and Neanderthal men and the long list of cultures with French names, past Stonehenge and the Beaker people, to end with the Iron Age men whose bodies are so strikingly preserved in Danish peat bogs. This is a smoothly and sensibly written piece, an excellent young people's introduction to the great theme. It is conservative in tradition, giving little credence to the new claims about the meaning of Stonehenge and other megaliths and no attention to the modern rereading of the cave paintings. The essential illustrations are here but there is no surplus.

Technology

KITES: AN HISTORICAL SURVEY, by Clive Hart. Frederick A. Praeger, Inc., Publishers ($12.50). "Few kite-flying nations have been so possessed as the Japanese by the desire to build larger and larger kites.... A *wan-wan* made in 1906 was twenty yards across and flew a tail 480 feet long. It weighed some 55 hundredweight. [It was] the property of the whole population of a district, who were summoned to bouts of kite-building by the ringing of temple bells. [It was] constructed of bamboo spars twelve inches in circumference." So runs one paragraph in this labor of love by an Australian scholar. Drawings, prints and photographs abound, and his learned bibliography is headed with the simple statement: "I have tried to list all books on kites published in English,...with the principal books in other European languages." This is an account of the kite so particular, so expert, so complete, so lively that it deserves young readers, who may come to hold it as their earliest model of what a monograph can be. It is the first good history of the kite. Franklin's electrical kite was a square silk kerchief; the altitude record, held by an eight-kite train of meteorological kites flown in 1919, is more than 32,000 feet; the Polynesians used kites in war and in fishing, as a means of divination and as a religious symbol; a fully nonrigid kite was patented by a NASA engineer in 1951. Professor Hart writes as he flies kites, with high pleasure, an expert's skill and an easy hand.

THE AFRICANS KNEW, by Tillie S. Pine and Joseph Levine. Pictures by Ann Grifalconi. McGraw-Hill Book Company ($3.50). "The Africans knew how to make...their tools of iron." "Today we make most of our tools of steel...mostly iron." "You can make your own tool to help you.... Try to push a large flat-headed nail...with a small rock.... You have a simple 'hammer.'" There are a dozen more such two-page spreads, telling something people did in old Africa, how we manage the same task today and something a small child can do for himself. The pattern is unvaried but agreeable. The colored wash drawings of drummers, smiths and dancers are attractive.

BUILDING A SKYSCRAPER, by Martin and Eve Marie Iger. Photographs by Martin Iger. Young Scott Books ($4.50). The steel-framed skyscraper, in which elevators have replaced stairs as automobiles have replaced walking in the suburbs, is the sign of the modern city—in Moscow, New York or Mexico City. Here is the photographic biography of a 41-story specimen now standing at 90

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Park Avenue in Manhattan. Some 80 photographs, from close-ups of the steelworker's hand signals to aerial shots of the whole towering neighborhood, form the frame of the exposition, which is built on and clothed with a text much as the steel frame grew out of a bedrock foundation, gained its mechanical core, concrete superstructure, glass-and-aluminum skin and elegant finish. The planners and schedulers are not forgotten. City children will recognize the art form; those who have never seen such a man-made cliff will be able to admire and learn. The numbers are worth knowing: 10,000 tons of steel, raised on a site of only nine-tenths of an acre; there were about 40 designers in all, counting architects, engineers and decorators; 600 men of many skills worked at the site for about two years. Cost: $40 million. This is a book full of content for readers in grades near the sixth.

SPACE ABC, by Lois Bruce. The Bobbs-Merrill Company, Inc. ($4). *Q* for *quasar* and *W* for *weightlessness*, so goes an entire alphabet, each letter illustrated by a two-page photographic spread from the headlines, the files of NASA or Mount Wilson and Palomar. The pages for *freefall* are graced by genuinely beautiful photographs of an entering test body, viewed once from far away and once from close up. *Space ABC* is marked by its publisher as being "for all ages"; if a very young reader is emotionally in the space age, the book will please him. Color photographs on the covers, all black and white within.

A BEGINNER'S GUIDE TO BUILDING AND FLYING MODEL AIRPLANES, by Robert Lopshire. Harper & Row, Publishers ($4.95). With a comic-book format, here used cheerfully but quite seriously, the reader is led into this craft much as though he had an experienced friend at his side. Glue, balsa wood from Ecuador, piano wire and razor blades are the stuff of this exacting work.

SECRETS OF MAGIC, ANCIENT AND MODERN, by Walter Gibson. Illustrated by Kyuzo Tsugami. Grosset & Dunlap, Inc. ($3.95). Brisk and straightforward in text, with pen drawings expressive or schematic by turns, this book explains some 70 illusions of history and of the modern stage. The dawn cry of the great statue of Memnon was heard and reported in antiquity by Pliny, Hadrian and many others. Silent since repairs under Septimius Severus about A.D. 200 (except to one party of English witnesses in 1820), the Pharaoh's image had spoken because the heat of the sun expanded air in a hollow within, which leaked through tiny cracks in the granite. Other formations are known to do much the same. The Indian rope trick is explained as well, partly by a healthy skepticism about the most enthusiastic anecdotes (particularly the idea of mass hypnosis) and partly by an account of a stretched-wire version that could work elegantly under some circumstances. How to saw a woman in half, how to levitate and how to make spirit photographs are all described in adequate detail. Not meant for seriously aspiring magicians, who need and can have access to much more detailed material, this book is a delightful peek behind the black curtain for any reader, young or old, who wonders about the magic of illusion. It is a pity that the book lacks any list of further readings.

SONG, SPEECH, AND VENTRILOQUISM, written and illustrated by Larry Kettlekamp. William Morrow & Company Inc. ($2.95). The mechanisms of speech and voice are taken apart for readers in the upper grades, with sensible model experiments and the tricky tests you can make with the black box of your own speech. Then the whole sense of understanding is put to real use, by building up a rationale from which anyone who will try hard, and practice, can become a genuine ventriloquist. There are even a few lines of properly old jokes. Original and intriguing, and possibly a low-key means of improving one's speech.

Exploration and Adventure

A DEAD WHALE OR A STOVE BOAT, by Robert Cushman Murphy. Houghton Mifflin Company ($8.50). The brig *Daisy* set sail out of New Bedford for the prairies of the sea in the sperm-whale hunt in the year 1911. She had a canny Yankee owner-skipper but no Yankee crew. Her mates and men ("No mainlanders among us—not one") were mostly black whalemen of skill and character from the Cape Verde Islands and the West Indies. Here you can see them in life, amid their ingenious engineless gear, courageously and relentlessly hunting their great prey, in a book of photographs whose "negatives were developed on shipboard in sea water" by the young author. Murphy, who was sailing with his new bride for a naturalist's season on the antarctic island of South Georgia, also looks out of these pictures, first as the eager, sober, rather dewy Brown graduate and 55 years later as the erect, white-haired scholar. The brave and beautiful bride is here too, and she seems even gayer now in her Long Island home than she does holding the violin for the photographer in Providence long ago.

This book is a link to a great past, a link of lovingly seen technical detail, a link to men who work with backbreaking effort in a common bond of danger and victory. It is eloquent in every line. The flow of history and man's life here become a single current. It is a classic document, a Melville for the eye, published after more than half a century of privacy.

ON THE ICE, by Peter Clarke. Photographs by Warren Krupsaw. Burdette & Company, Inc. ($6.95). Modern exploration is powerful beyond the dreams of the past; the price we pay for that power is ugliness and fragmentation. This conclusion comes clear in this journalistic account of U.S. Navy operations in Antarctica, written in a prosy style, although always personal and firsthand. The men who handle the tractors and the oil drums and the canned soups are here, good-humored and competent. The South Pole itself is visible, with instrument masts and two flagpoles, one for Amundsen the discoverer and one for the Americans who have occupied the high post on the ice continuously since 1956. A young Navy technician at a coastal station fell and suffered internal injuries during the dark nights of June, 1966; a plane was sent out from Rhode Island to pick him up, accomplishing the second landing ever made in the antarctic dark. He was flown out to New Zealand for successful surgery.

The sense of intimacy from the homely words and the direct personal photographs is strong. Beauty is there, but only in long shots and aerial views. The questing is now refined, institutional, scientific, remote. Whoever wants to know about this corporate adventure—which is our closest analogue to the future voyages to the moon—can see it here, told as it is.

TO THE PACIFIC WITH LEWIS AND CLARK, by Ralph K. Andrist with E. R. Bingham. American Heritage Publishing Co. Inc. ($4.95). What a breed of men were the 18th-century planters of Virginia's Albemarle County! Their leader, Thomas Jefferson, was determined to send an American expedition through our new lands to the Oregon coast. He chose the young army officers Lewis and Clark, whose families were his neighbors up-country, to make the journey. This book, richly illustrated with engravings, maps, photographs and paintings in color, is a lively and simple account of that great expedition. "Ocean in view! O! the joy!" wrote Clark on November 7, 1805. The book is indexed and has an excellent page of references, with an account of where the original materials are and of the highway markers that trace the route today.

THE REMARKABLE RIDE OF THE ABERNATHY BOYS, by Robert B. Jackson. Henry Z. Walck, Inc. ($3.25). In 1910 two brothers, aged six and 10, rode their cowboy ponies, never more than 50 miles a day, from Cross Roads, Okla., to New York City to visit Theodore Roosevelt. They stopped off to visit the Wright brothers in Dayton, Ohio. Their father, who was a wolf-hunting guide and a U.S. marshal, knew T. R., and the idea of the trip was his. The motherless family returned west by automobile. The boys drove a red one-cylinder Brush runabout (with two forward speeds, a wooden body and wooden axles) they had bought out of their newsreel earnings; Father traveled in a big Maxwell with a chauffeur. The horseback trip took two months, the automobile one three weeks. These two boys are living today, cheerful, solid citizens of Texas. The sense of modern history is made simple enough for young grade school readers to grasp in this indubitable but incredible little story. There are plenty of period pictures.

OOMINGMAK: THE EXPEDITION TO THE MUSK OX ISLAND IN THE BERING SEA, by Peter Matthiessen. Hastings House Publishers, Inc. ($3.95). This is a traveler's tale, as much about men—men with their "green airplanes and yellow parkas and a blue canoe" in a muted landscape—as about animals. It is so limpid, rhythmic and honest an account of a small expedition that it can be read by young readers or aloud in the family. The purpose of the journey was a roundup of musk-ox calves (the musk-ox is called *oomingmak* in the Eskimo tongue) as a step toward domesticating this species for its fine wool. The musk-ox is in center stage, but helicopters, the Eskimos and the great reindeer herds give strong support.

THE OCEANS: A TREASURY OF THE SEA WORLD, edited by Seon Manley and Gogo Lewis. Doubleday & Company, Inc. ($3.95). An anthology of wide range, centering on adventure but opening with Rachel Carson on the origins of the sea and closing with Samuel Eliot Morison's sail into Northeast Harbor at the end of a golden August day. Submarines at war, the Maelstrom, a forced voyage in an open boat, Cousteau's skin diving, Thoreau on a shipwreck and Jack London on surfing ("Bit the sea's breakers, master them, and ride upon their backs as a king should") are half of this excellent set of readings for boys and girls who know the sea.

ACROSS THE OCEAN SEA: A JOURNAL OF COLUMBUS'S VOYAGE, by George Sanderlin. Illustrated by Laszlo Kubinyi. Harper & Row, Publishers ($4.95). The core of this book is a helpfully annotated translation of the famous day-by-day summary made by Las Casas of the now-lost journal of Columbus. This account, with its fixity of purpose and its confusions, is preceded by texts of the legends of St. Brendan, by bits of Marco Polo and of the sagas of Leif and Eric and Bjarni, and is followed by a clear account of the 20 years after Columbus when the Americas became recognized and set firmly in maps as a New World. Columbus shot the stars but found the latitude of the Bahamas to be that of Peking; he mistook another star for the Pole Star. Indeed, he wished himself farther north, where the great cities of China were. Anyone who likes exploration will enjoy this book, whose firsthand documents are made readable by the author's careful and interesting arrangement and commentary. The line drawings and maps are good.

GIANTS IN THE SKY, by Norman Richards. Illustrated by Robert and Corinne Borja. Childrens Press, Inc. ($5). Henri Giffard flew a steam-driven hydrogen balloon a few miles outside Paris in 1852. The flight began the history of dirigible balloons, now represented in all the world by a couple of aging blimps. This book, handsomely decorated with block prints and photographs, tells the story of the rise and fall of the great dirigibles. Here is Count Zeppelin and his fleet, the terror of London in 1916. Here is the story of the airships of Britain and the U.S., huge silvery cigars floating silently over the cities of the 1930's but all wrecked by fire or storm. The triumph of the *Graf Zeppelin* in carrying passengers around the world in comfort in 21 days and maintaining for years a scheduled transatlantic run from Germany to Brazil is told. She carried 13,000 passengers without a fatality. Her successor, the *Hindenburg*, a new luxury ship with a dozen routine ocean crossings on the logbook, burned in one horrible moment. No rigid airship has flown since 1937, and even the hundreds of patrol blimps of World War II have become all but extinct. The airship is a victim of scale; big enough and light enough to be useful, she spans too much of irregular winds to withstand their shear.

This is another fascinating history, aimed at young readers, but to a good many parents it will bring the pungency of nostalgia. They were beautiful, those airships.

MANNED SPACECRAFT, by Kenneth Gatland. The Macmillan Company ($3.50). Billed as "the pocket encyclopedia of spaceflight in color," this small, dense volume is written by a British space journalist of long standing and is illustrated by lacquer-bright airbrush paintings with a remarkable fineness of detail. The core of the book is 80 pages of pictures showing, among much else, Gemini and Atlas, *Vostok* and *Voskhod 2*, crewmen in their gear and breathtaking views of the earth-map below. A knowing and accurate text in operational depth and jargon is appended. This will be irresistible for its fans but may be faintly repellent to everyone else. A slight suspicion of retouching on the space photographs and a rather credulous account of some Russian space politics are flaws in a remarkably up-to-date work of reference (it contains the Gemini fire but not the Paris display of the *Vostok* rocket).

CROSSROAD PUZZLERS, by David Webster. The Natural History Press ($3.50). Here is a book of a new sort. It contains about 150 photographs of the highway landscape: signs, dented cars, long-legged trucks, leaning hydrants, skid marks and much more. Each picture is captioned with a sharp question. A truck hood has a company name across its front—in mirror writing. Why is the name printed backward? The answers are given on later pages, often with another question implied. This is Sherlock Holmes on the highway, and a better scheme for teaching anyone how not only to see but also to observe and to seek order in his observations would be hard to find. The book is leavened with a few wry and cheerful jokes. There is a final section that is pictureless but illustrated with words and numbers. There are games and tasks—often computations—that can be done on the road. An army tank, one table of comparisons shows, gets only a quarter of a mile to the gallon. Altogether a work of an original and expert kind, the very ground matter of science, in the most commonplace of American contexts.

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ANNUAL INDEX

The following index lists all the authors and articles that appeared in SCIENTIFIC AMERICAN *during 1967. Also indexed are "Mathematical Games," "The Amateur Scientist" and the principal book review in each issue.*

AUTHORS

ARTICLES

MATHEMATICAL GAMES

THE AMATEUR SCIENTIST

BOOKS

BIBLIOGRAPHY

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

INFECTIOUS DRUG RESISTANCE

EVOLUTIONARY RELATIONSHIPS OF R FACTORS WITH OTHER EPISOMES AND PLASMIDS. T. Watanabe in *Federation Proceedings,* Vol. 26, No. 1, pages 23–28; January–February, 1967.

INFECTIVE HEREDITY OF MULTIPLE DRUG RESISTANCE IN BACTERIA. Tsutomu Watanabe in *Bacteriological Reviews,* Vol. 27, No. 1, pages 87–115; March, 1963.

THE EARLIEST APES

A CRITICAL REAPPRAISAL OF TERTIARY PRIMATES. Elwyn L. Simons in *Genetic and Evolutionary Biology of the Primates: Vol. I,* edited by John Buettner-Janusch. Academic Press Inc., 1963.

NEW FOSSIL APES FROM EGYPT AND THE INITIAL DIFFERENTIATION OF HOMINOIDEA. E. L. Simons in *Nature,* Vol. 205, No. 4967, pages 135–139; January 9, 1965.

ORIGINS OF MAN: PHYSICAL ANTHROPOLOGY. John Buettner-Janusch. John Wiley & Sons, Inc., 1966.

X-RAY STARS

OBSERVATION OF X-RAY SOURCES OUTSIDE THE SOLAR SYSTEM. Riccardo Giacconi and Herbert Gursky in *Space Science Reviews,* Vol. 4, No. 2, pages 151–175; March, 1965.

COSMIC X-RAY SOURCES, GALACTIC AND EXTRAGALACTIC. E. T. Byram, T. A. Chubb and H. Friedman in *Science,* Vol. 152, No. 3718, pages 66–71; April 1, 1966.

EXPERIMENTAL X-RAY ASTRONOMY. Bruno Rossi in *Perspectives in Modern Physics,* edited by R. E. Marshak. Interscience Publishers, 1966.

A MEASUREMENT OF THE LOCATION OF THE X-RAY SOURCE SCO X-1. H. Gursky, R. Giacconi, P. Gorenstein, J. R. Waters, M. Oda, H. Bradt, G. Garmire and B. V. Sreekantan in *Astrophysical Journal,* Vol. 146, No. 1, pages 310–316; October, 1966.

ON THE OPTICAL IDENTIFICATION OF SCO X-1. A. R. Sandage, P. Osmer, R. Giacconi, P. Gorenstein, H. Gursky, J. Waters, H. Bradt, G. Garmire, B. V. Sreekantan, M. Oda, K. Osawa and J. Jugaku in *Astrophysical Journal,* Vol. 146, No. 1, pages 316–321; October, 1966.

SOME NEW CHANNELS FOR ASTRONOMY. P. Morrison in *Perspectives in Modern Physics,* edited by R. E. Marshak. Interscience Publishers, 1966.

ZONE REFINING

CONTROL OF COMPOSITION IN SEMICONDUCTORS BY FREEZING METHODS. C. D. Thurmond in *Semiconductors,* edited by N. B. Hannay. Reinhold Publishing Corporation, 1959.

PRINCIPLES OF ZONE-MELTING. W. G. Pfann in *Transactions of the American Institute of Mining and Metallurgical Engineers,* Vol. 194, pages 747–753; July, 1952.

ZONE MELTING. William G. Pfann. John Wiley & Sons, Inc., 1966.

ZONE MELTING. Hermann Schildknecht. Academic Press, 1966.

ZONE MELTING OF ORGANIC COMPOUNDS. E. F. G. Herington. Blackwell Scientific Publications, 1963.

HIGH-ENERGY SCATTERING

COMPLEX ANGULAR MOMENTA AND PARTICLE PHYSICS. Euan J. Squires. W. A. Benjamin, Inc., 1963.

QUARKS AS ADDITIVE CONSTITUENTS OF MESONS AND BARYONS. Leon Van Hove in *Comments on Nuclear and Particle Physics,* Vol. 1, No. 1, pages 8–12; January, 1967.

TRACKING DOWN PARTICLES. R. D. Hill. W. A. Benjamin, Inc., 1963.

THE VIBRATING STRING OF THE PYTHAGOREANS

ART AND ARCHITECTURE IN ITALY: 1600–1750. Rudolf Wittkower. Longmans Canada Ltd., 1959.

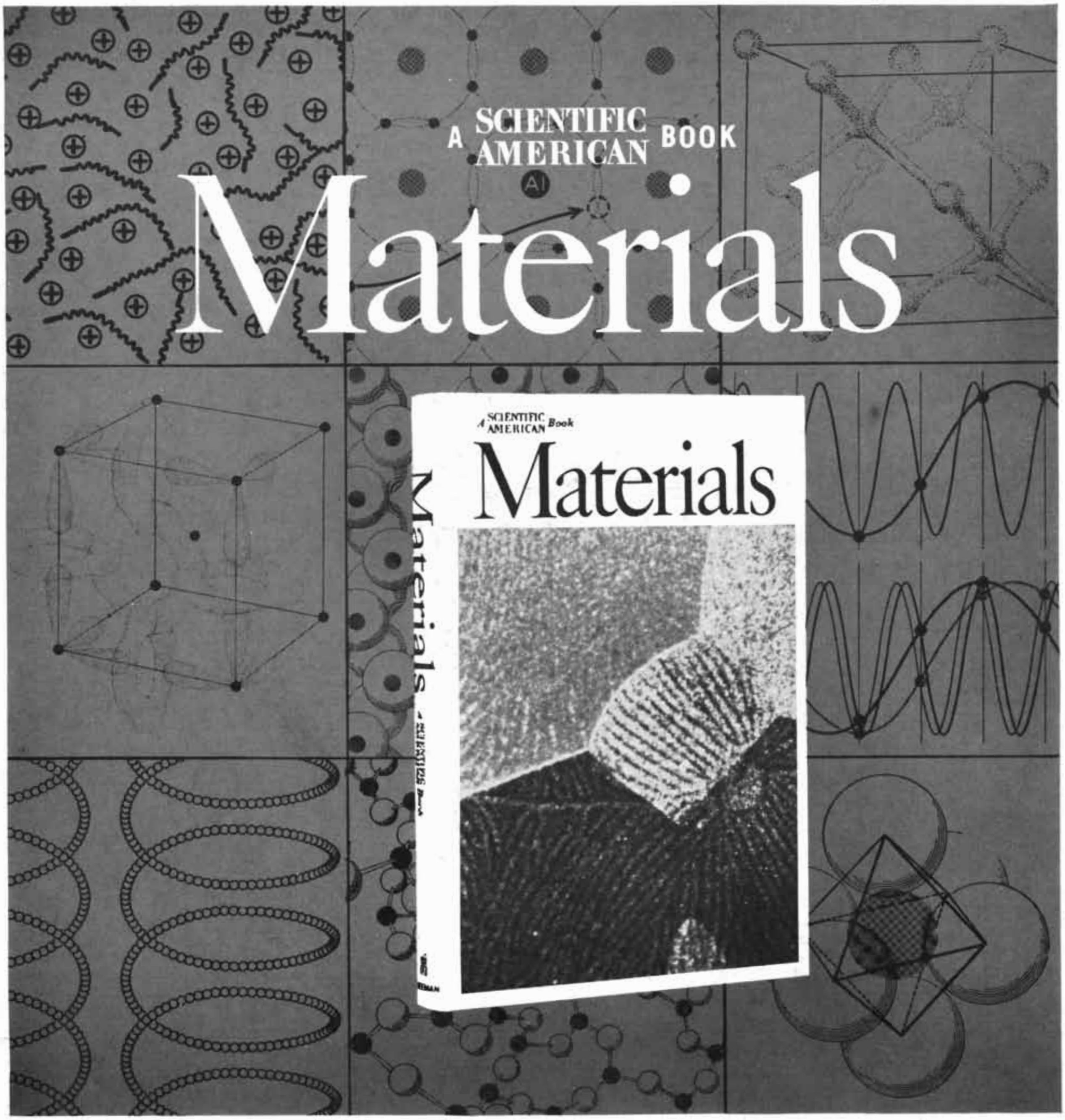
CONVERSATIONS WITH STRAVINSKY. Igor Stravinsky and Robert Craft. Doubleday & Company, Inc., 1962.

THE HARMONIES OF THE WORLD: V. Johannes Kepler in *Great Books of the Western World: Vol. XVI,* edited by Robert Maynard Hutchins. Encyclopaedia Britannica, Inc., 1952.

THE MATHEMATICAL BASIS OF THE ARTS. Joseph Schillinger. Philosophical Library, 1948.

MUSIC IN THE MEDIEVAL AND RENAISSANCE UNIVERSITIES. Nan Cooke Carpenter. University of Oklahoma Press, 1958.

THE NEW COLLEGE ENCYCLOPEDIA OF MUSIC. J. A. Westrup and F. L. I. Harrison. W. W. Norton & Company,


A SCIENTIFIC AMERICAN BOOK
Materials
Al
A SCIENTIFIC AMERICAN Book
Materials
Materials

Inc., 1960.

THE UNTUNING OF THE SKY: IDEAS OF MUSIC IN ENGLISH POETRY. John Hollander. Princeton University Press, 1961.

NON-CANTORIAN SET THEORY

AN INTRODUCTION TO THE FOUNDATIONS AND FUNDAMENTAL CONCEPTS OF MATHEMATICS. Howard Eves and Carroll V. Newsom. Holt, Rinehart and Winston, 1965.

A PROOF OF THE INDEPENDENCE OF THE CONTINUUM HYPOTHESIS. Dana Scott in *Mathematical Systems Theory,* Vol. 1, No. 2, pages 89–111; May, 1967.

SET THEORY AND THE CONTINUUM HYPOTHESIS. Paul J. Cohen. W. A. Benjamin, Inc., 1966.

WHAT IS CANTOR'S CONTINUUM PROBLEM? Kurt Gödel in *Philosophy of Mathematics: Selected Readings,* edited by Paul Benacerraf and Hilary Putnam. Prentice-Hall, Inc., 1964.

THE WATER BUFFALO

A COMPILATION OF AVAILABLE DATA ON THE WATER BUFFALO. Bradford Knapp. International Cooperation Administration, 1967.

SEASONAL VARIATIONS IN REACTION TIME AND SEMEN QUALITIES OF BUFFALO BULLS. N. S. Kushwara, D. P. M. Mukherjee and P. Buhattacharya in *Indian Journal of Veterinary Science and Animal Husbandry,* Vol. 25, Part 4, page 327; 1955.

THE WATER BUFFALO IN INDIA AND PAKISTAN. David C. Rife. International Cooperation Administration, 1959.

MATHEMATICAL GAMES

THE COMPLEAT STRATEGYST: BEING A PRIMER ON THE THEORY OF GAMES OF STRATEGY. J. D. Williams. McGraw-Hill Book Company, Inc., 1954.

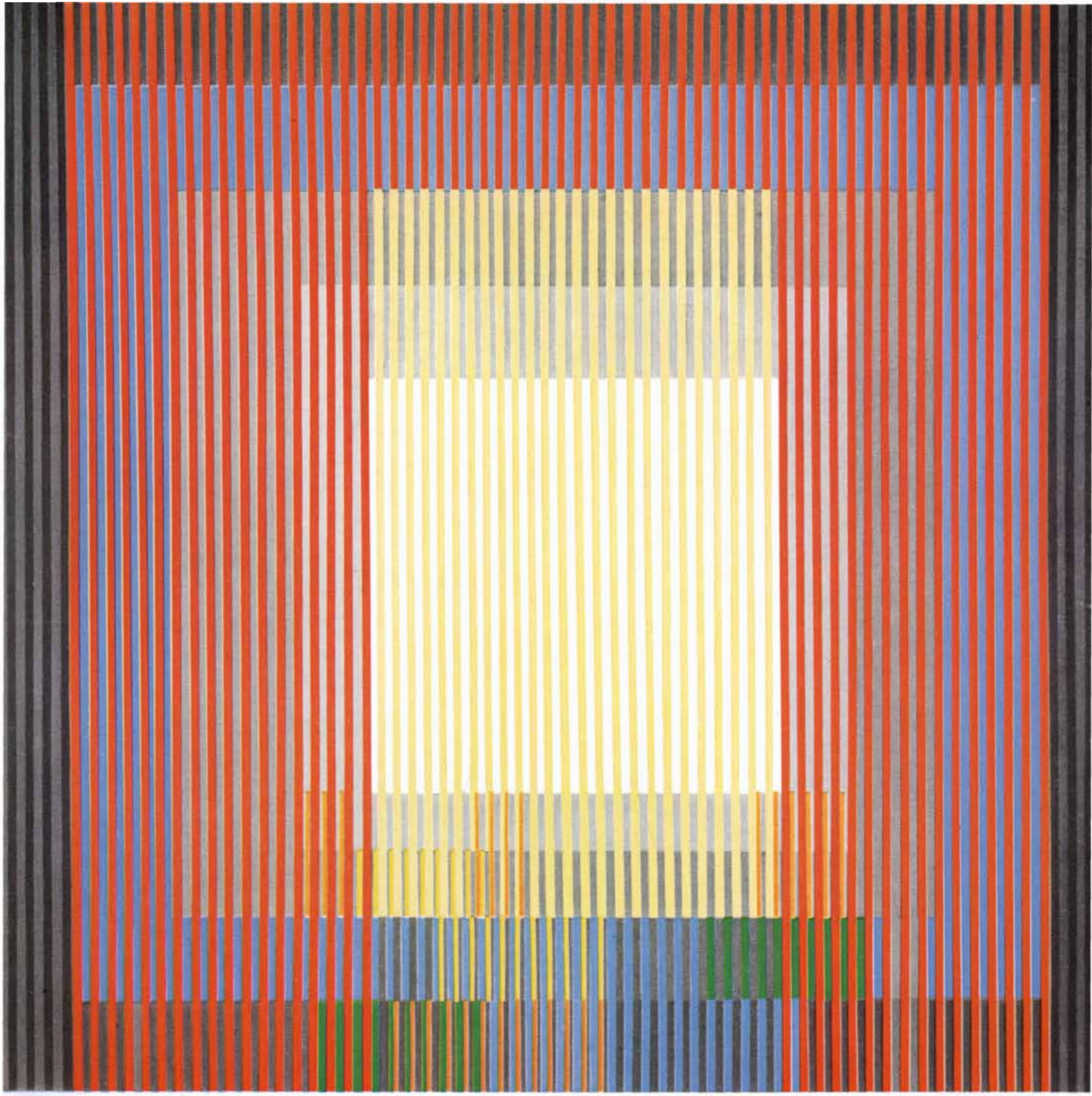
GAMES OF STRATEGY: THEORY AND APPLICATIONS. Melvin Dresher. Prentice-Hall, Inc., 1961.

THE USE AND MISUSE OF GAME THEORY. Anatol Rapoport in *Scientific American,* Vol. 207, No. 6, pages 108–118; December, 1962.

THE AMATEUR SCIENTIST

BEGINNING IN ARCHAEOLOGY. Kathleen M. Kenyon. Frederick A. Praeger, 1952.

THE SCIENTIFIC AMERICAN BOOK OF PROJECTS FOR THE AMATEUR SCIENTIST. C. L. Stong. Simon and Schuster, Inc., 1960.



the troubled air

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