SCIENTIFIC
AMERICAN

KNOT-TYING FISH

SIXTY CENTS

February 1966


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CELANESE

new size
new technology
new symbol
same basic principles

Important symbols—like the flags of nations or the trademarks of corporations—stand for basic principles. They represent the ideas that tie together a great diversity of people and things in common cause.

Our principles are simple:

We believe that every single one of our employees is in service to the customer; that our success depends upon the freedom of each employee to develop all his resources of imagination, skill and talent; that we must explore every opportunity as a world opportunity; and that we must work so efficiently that we can earn enough profits on the savings invested in us to help us continually enlarge our capabilities for outstanding products and services.

These beliefs have helped us bring to market—within a generation—an impressive array of new products to make life a little easier or a little pleasanter for people around the world. By finding new ways through chemistry to meet man's ever expanding needs, Celanese has grown into a major producer of chemicals, man-made fibers, surface coatings and plastics.

We have moved closer to the consumer through diversification into paints, plastic housewares and the retailing of gasoline and oil. In the process of growing we have become important producers of pulp and petroleum—two raw materials basic to almost everything we make.

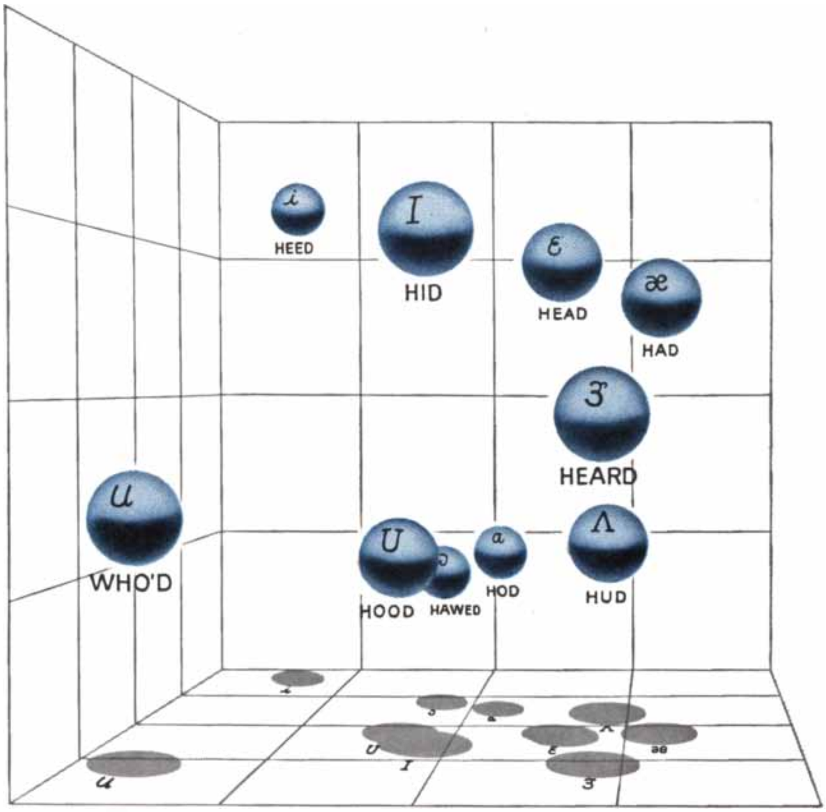
With the addition of many new names to our family of companies, we felt the need for a new, modern but classic device to suggest the unity that underlies our changing and expanding world operations. And in a broader sense, to stand for the things that haven't changed—our basic principles.

You'll be seeing our new symbol in many places in the months and years ahead. It's the sign of a world enterprise, growing fast by putting chemical science to work for people.

CELANESE CORPORATION, 522 5th AVE., N.Y.

Report from

BELL LABORATORIES



Representation in subjective space of the proximities (i.e., "nearness" or "farness") among ten vowel sounds, indicated at left by phonetic symbols. Test subjects heard these vowels in words like heed, had, hid, etc., and were asked to identify them. Pairs of vowels frequently confused are considered "near" to each other; other pairs which were seldom confused are regarded as "far apart." This computer solution displays these spatial relationships, relating each vowel to every other vowel, in a form easily visualized.

"SUBJECTIVE SPACE"—A NEW METHOD OF UNCOVERING MEANING

It is easy to record people's opinions and reactions, but sometimes it is hard to extract usable information from such subjective data. Valid meaning might be clouded by a mass of seemingly inexact information.

Test subjects listening to telephone channels of varying quality. Subjects heard test sentences transmitted over pairs of channels; for each pair they indicated, by pressing a button, which of the two they preferred. Signals from buttons were used to key-punch cards, which were then processed with adaptations of the "subjective space" program developed at Bell Laboratories.

A new method of analyzing data to reveal such meaning has been developed by R. N. Shepard and adapted for different uses by several of his fellow researchers at Bell Telephone Laboratories. With this method, the underlying structure of the data is displayed in the form of a spatial representation. The illustration above, for example, shows such a representation obtained for ten different sounds—namely, ten words differing only in the vowel sound. This representation was obtained by an analysis of the subjective similarities among these sounds as revealed by how frequently listeners confused each pair of words. In the resultant "subjective space," pairs like *hod* and *hawed* that were frequently confused by listeners are represented as close together, whereas pairs like *heed* and *hud* that were rarely confused are represented as far apart.

In this spatial arrangement, the underlying structure is revealed more clearly than with conventional methods of presenting data. Moreover, the dimensions of the subjective space often provide information about which physical properties of the stimuli are the most critical psychologically. (For example, the three dimensions for the above ten vowel sounds were found to correspond roughly to the frequencies of the first three resonances of the human vocal tract.)

The method devised for finding such spatial representations uses an iterative process programmed for a high-speed digital computer. It seeks an optimum configuration of points in a space of the smallest possible number of dimensions in which the given data are represented in the interpoint distances. Solutions in one, two, and three dimensions are conveniently displayed by a visual computer output. As a result, the psychologically significant dimensions of the stimuli—which might not be evident from traditional methods of analysis—can often be identified simply by inspection. The method is quite general: the data can be subjective judgments of similarity or can be frequencies of actual confusions, and the stimuli can be colors, sounds, or even communication circuits varying in quality.

Bell Telephone Laboratories
Research and Development Unit of the Bell System

Established 1845 **SCIENTIFIC AMERICAN** February 1966 Volume 214 Number 2

ARTICLES

DEPARTMENTS

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Lab research or automatic monitoring

For high-accuracy, high-resolution laboratory-type temperature measurements or for monitoring a series of industrially oriented temperatures, the Dymec Quartz Thermometer introduces capabilities never before available:

Direct digital readout with up to 0.0001° resolution; high-accuracy absolute or difference measurements; automatic or manual scanning of multiple temperature points, accurate measurements at distances from the thermometer; outputs for recording on printed strip, punched tape, cards, digital magnetic tape or strip-chart recorder.

With the DY-2801A, you can measure degrees C or F without bridge balancing, conversion charts, temperature references or computer processing. The actual technique involves measurement of the frequency of a temperature-sensitive quartz oscillator, rather than voltages or resistances as associated with thermocouples or platinum resistance devices.

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The DY-2801A has two probes and variable resolution to 0.0001°, and is priced at $3250. The less expensive 2800A is available for $2250 if your requirement demands a single probe and 0.1° resolution (optionally 0.01°).

A nearby Hewlett-Packard field engineer will demonstrate the thermometer for you, or you can get complete information and data relative to lab or monitoring applications by filling out the coupon and mailing it to Hewlett-Packard Dymec Division, 395 Page Mill Road, Palo Alto, California 94306. Phone (415) 326-1755. TWX 910-373-1296.

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THE COVER

The painting on the cover shows a hagfish, enormous numbers of which live on the bottom of the oceans (see "The Hagfish," page 82). Here the hagfish has tied itself into a half hitch, a feat it performs routinely. When the hagfish is alarmed, it secretes large quantities of a tenacious slime; it wipes itself clean by forming a knot and pulling itself through the loop. The hagfish also ties knots to exert leverage in pulling flesh out of dead or dying fish, on which it feeds. The large single opening at the head end of the hagfish at upper right in the painting is not the animal's mouth but its nostril; the mouth is the smaller opening behind the protruding barbels. The large pores along the sides of the fish are the exits of its gill sacs; the smaller pores are for secreting slime. There are 24 known species of hagfish. Shown in the painting is *Eptatretus stoutii,* a species that lives in the Pacific.

THE ILLUSTRATIONS

Cover painting by Thomas Prentiss

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Being a Hertz girl has its moments. Getting compliments isn't one of them.

In fact, the better we do, the less we're noticed.

We look at it this way—you shouldn't have to be concerned with anything when you rent a car from us. You have more important things on your mind.

But we haven't.

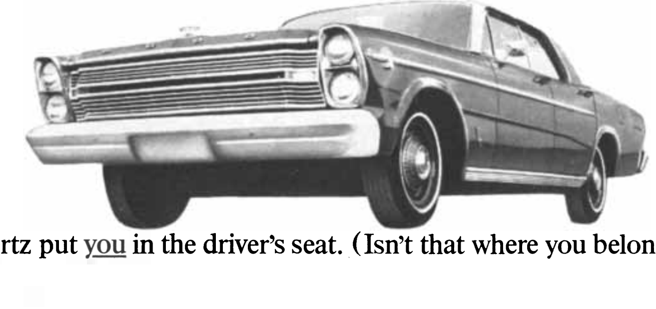
So we do everything humanly possible to make certain that our shiny new Fords and other cars are in as near-perfect condition as we can make them. And that the car you want is ready and waiting when and where you want it.

But we don't think our job stops there.

We're also never too busy to help you find the quickest way to where you want to go. Or answer any other questions you might have.

You might say our business is to help you concentrate on yours. As for compliments, say you want one of our cars.

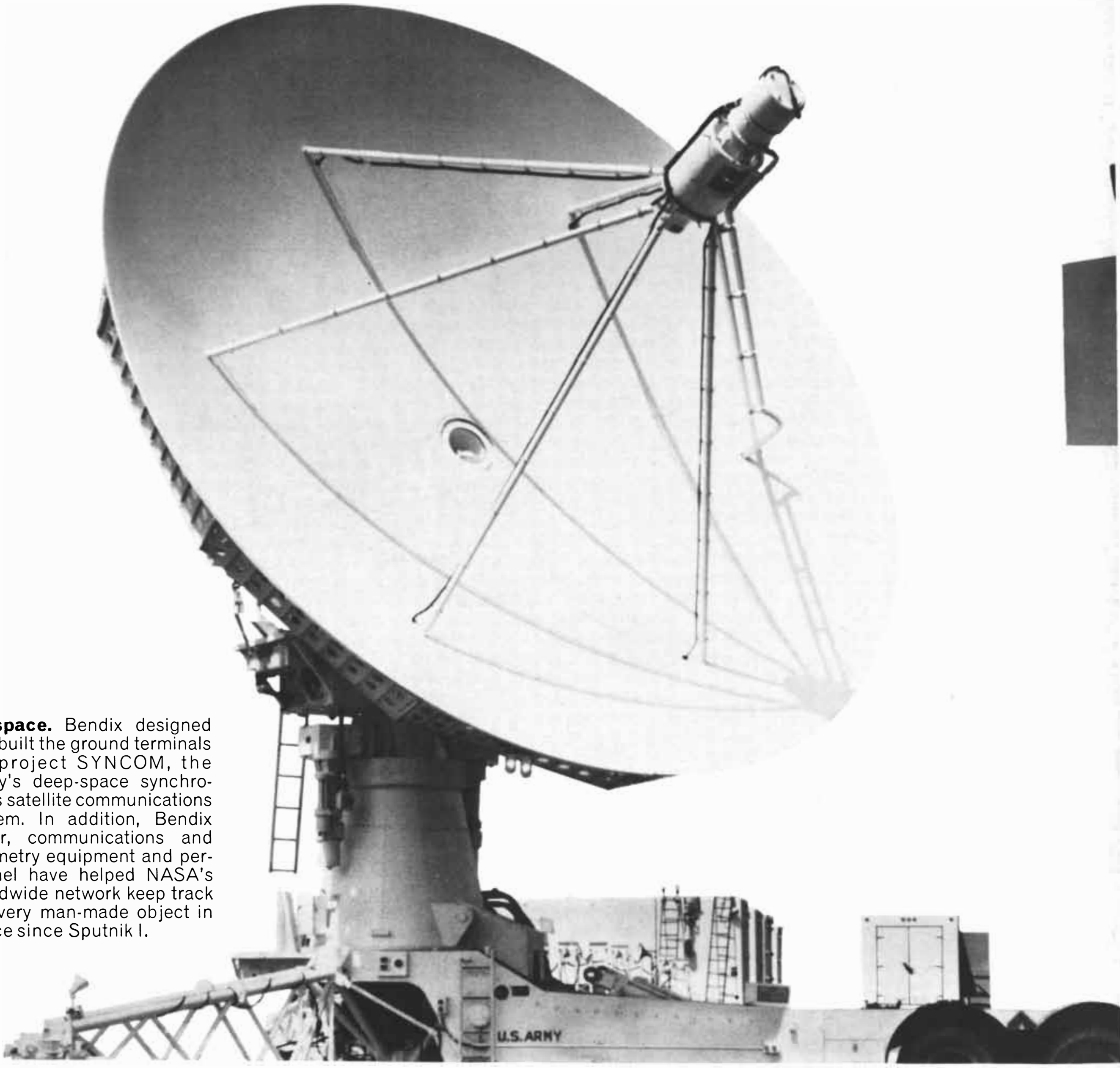
That's the nicest thing you could say.



Let Hertz put you in the driver's seat. (Isn't that where you belong?)

HERTZ
RENT A CAR

Bendix is the kind of company that keeps people in touch everywhere.



In space. Bendix designed and built the ground terminals for project SYNCOM, the Army's deep-space synchronous satellite communications system. In addition, Bendix radar, communications and telemetry equipment and personnel have helped NASA's worldwide network keep track of every man-made object in space since Sputnik I.

On the highway. Forty different models of 1966 cars and trucks with Bendix factory-installed AM and FM radios will keep people informed and entertained everywhere. Bendix has manufactured over 13 million car radios to date.

On the water. Pleasure boat skippers rely on Bendix radio-telephones, as well as Bendix radio direction finders, radar systems, depth sounders, automatic pilots, and fume detectors.

In NASA's tracking network. During manned space flight, Bendix-built consoles give a detailed, running report of each astronaut's physical condition and the operational performance of the spacecraft.

In the air. Our Trophy Line of navigation and communication equipment offers pilots and owners of business and private aircraft new savings in weight and space, as well as the increased reliability of solid state circuitry.

We design and produce communications equipment and systems for every basic market we serve: space, missiles, automotive, aviation, oceanics—even automation where Bendix-built machines transmit instructions to other machines. In each area, we provide *total* capability—from instrument design to production . . . from systems research to installation. Our work in communications demonstrates again that the heart of our business is creating new ideas and developing them to maximum usefulness—whether we're serving as creative engineers . . . manufacturers . . . or professional problem-solvers for industry and government.

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THE BEST TELESCOPES WILL HAVE QUARTZ MIRRORS

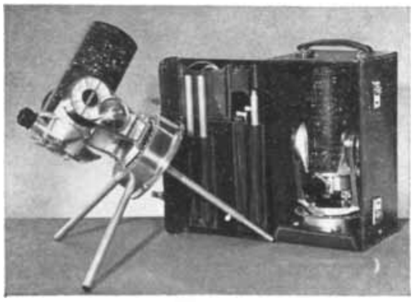
Half the Questar telescopes we now produce have mirrors made of quartz. We started using this precious material back in 1957 because quartz mirrors are the very best obtainable. When we take one from a warm room into colder outdoor air, quartz resists the thermal shock about 5 times better than Pyrex low-expansion glass. The superiority of quartz lies in this greater stability of the crystal.

The price of fused-quartz disks is awfully high because they are terribly difficult to construct. A raw disk 61 inches in diameter costs $250,000. Since the cost and weight of such disks, like 3-dimensional objects generally, increases as the cube of a dimension, and not as the square, you can readily understand why there are only a few hundred telescopes with quartz mirrors in the entire world. We ourselves have probably made most of them.

As you may know, we still have to make each aspheric set of Questar optics at least 3 times, until its resolving power is astonishing, and each will support images that do not break down at more than 800 diameters. This unusual ability to resolve, coupled with small aperture, allows these little fellows to pierce indifferent seeing like a thin rapier when larger apertures are more severely damaged by heat waves in the air.

This is the Questar idea, the Questar secret. In the 8 years of research we spent before marketing our product, we sought and found the best size to make it; we looked for the point where the greatest number of favorable factors came together. That point turned out to be at only 3.5 inches aperture instead of the 5 inches with which we started. Our portable telescope proved to be most efficient when delightfully small in size but of transcendent quality.

This very smallness becomes another favorable factor. You yourself may now enjoy the luxury of owning a real quartz-mirrored telescope for only $100 extra.



Questar is the finest and most versatile small telescope in the world. Prices begin at $795. Send for your copy of the new 40-page booklet with 8 pages of color and much general information, with essays on optics, seeing and telescopic photography. One dollar postpaid in U. S., Mexico and Canada. By air to West Indies and Central America, $2.30. By air to Europe, N. Africa and S. America, $2.50. By air to Australia and elsewhere, $3.50.

QUESTAR

BOX 20 NEW HOPE, PENNSYLVANIA

LETTERS

Sirs:

I greatly enjoyed E. Donnell Blackham's article "The Physics of the Piano" [SCIENTIFIC AMERICAN, December, 1965]. In reading the article I observed an extraordinary fact: it begins on page 88, which is of course the number of keys in the modern piano. Surely this is carrying the spirit of your department "Mathematical Games" too far!

WINIFRED D. DUFFY

Forest Hills, N.Y.

Sirs:

"Microelectronics," by William C. Hittinger and Morgan Sparks [SCIENTIFIC AMERICAN, November, 1965], is timely and most interesting.

It is unfortunate that Hittinger and Sparks did not consider the history and origin of microelectronics in sufficient detail to make clear in their presentation the answer to the question: How much of the "new technology" is really so vital to microelectronics that under no circumstances could it be omitted? In reply, the essential element is that of so-called oxide masking, a discovery made more than 10 years ago by a chemist at the Bell Telephone Laboratories, Carl Frosch.

The journal and magazine literature now abounds with pictures of microelectronics and integrated electronics. When in color, these pictures always show the ubiquitous green, blue and pink protective masking silicon dioxide. Frosch first discovered the use of these oxides on silicon electronic devices; he showed that these oxides protected the silicon from thermal erosion; he found that they afforded a means for defining the geometry and structure of the "new electronics"; in addition, he proposed that they gave a natural means for the protection of the surface of the new electronics from the contamination of the "outside" world (outside the silicon electronic device). Here is the unique technological ingredient in microelectronics.

Obviously the refined, sophisticated exploitation of oxide masking has in the past 10 years received further contributions from many workers. But Frosch set it up with his discovery, and microelectronics could not exist without it; on the contrary, many other admit-

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HOW AN RCA ELECTRON TUBE

recovers fortunes from "Davy Jones"

A "spent" experimental torpedo settles to the bottom by accident or by design. Is this investment lost forever?

A rocket booster splashes into a 300 fathom trench in the South Atlantic. Can the full story of its launch and flight ever be told? Can scientists and engineers correct the design or replace the faulty part for the next tests?

The answers depend on recovery of the equipment. Until recently, salvaging hardware "on the bottom" was almost impossible. Now, thanks to underwater TV, recoveries are made almost daily...cheating "Davy Jones" out of millions.

Watertight TV cameras—in remote-controlled deep-sea recovery vehicles like the one below—scan the ocean floor for lost material, relay TV pictures of it to the "mother ship" on the surface. Once located, the sunken objects are picked up by a giant hydraulic claw on the recovery vehicle, then returned to the waiting ship above. With such systems there are no problems of compression and decompression faced by human divers...no limitations on the length of search.

Making possible deep-sea TV surveillance is a light-sensitive RCA TV camera tube known as a "vidicon"... a tiny replica of TV studio camera tubes that send programs to your home. About 5 inches long and an inch in diameter, this compact, high-performance RCA electron tube delivers sharp, full-fidelity TV pictures under the worst conditions: tremendous pressures...heavy shock, vibration and buffeting...and minimal light.

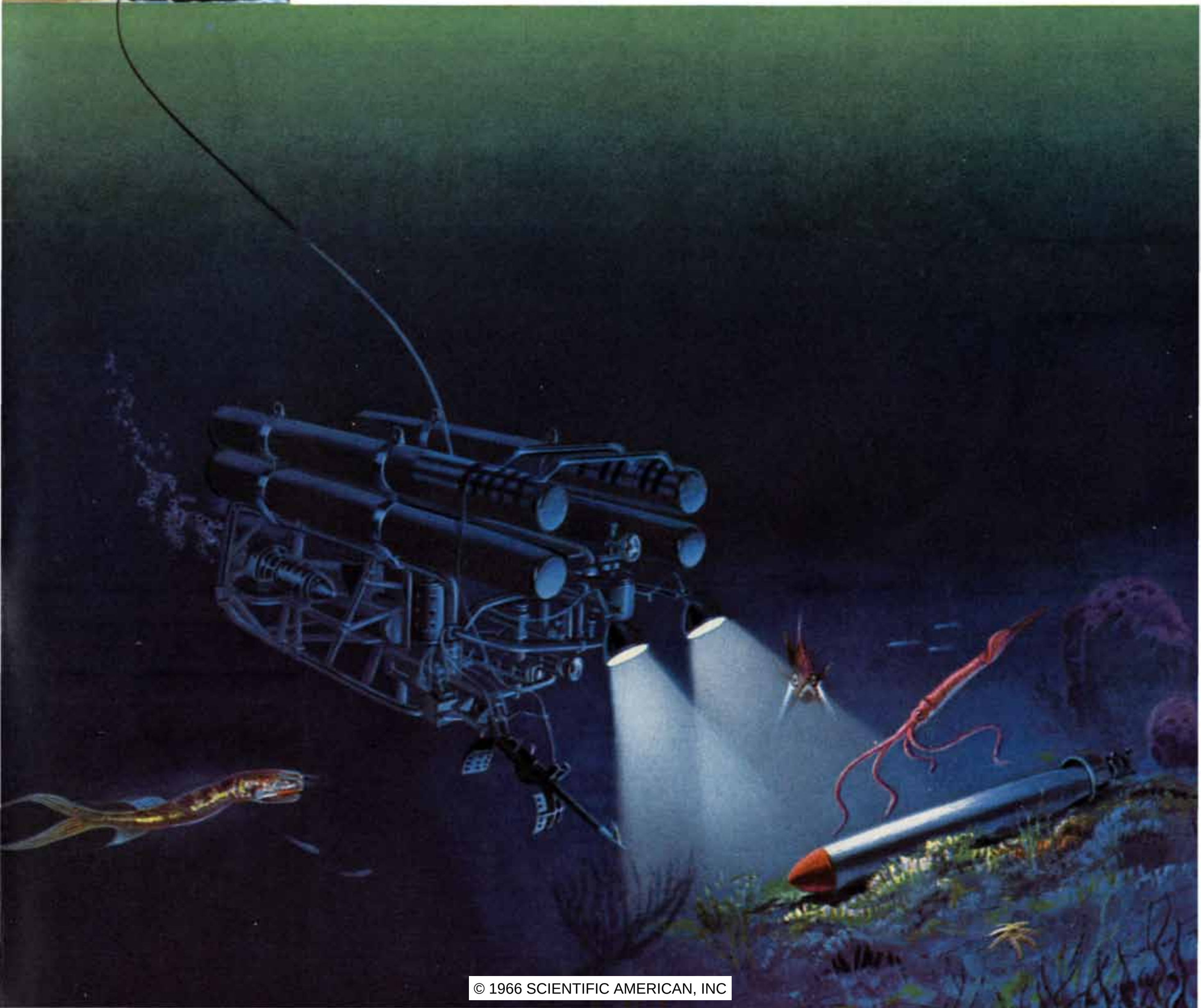
This dramatic use of the TV vidicon is another example of how RCA products and skills developed originally for home entertainment and education can be adapted to the needs of science, industry and the nation's defense.

Super-sensitive RCA underwater TV vidicon tube needs only 500 watts of light to produce sharp, clear TV pictures...even at depths as great as 2,000 feet.

RCA ELECTRONIC COMPONENTS AND DEVICES

The Most Trusted Name in Electronics

Self-propelled, cable-controlled U.S. Navy undersea recovery vehicle locates a lost torpedo, then picks it up and returns it to the surface.



Western has been shipping "progress" since 1888

When the Star of India was plying the seas, Western was already packaging imagination and exporting experience. Today, Western is international in scope, almost unlimited in engineering capability, yet still offering its basic product: ideas and the machinery to make them work.

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Everett, Washington; Belmont, Lynwood, Pasadena, Los Angeles, California; Houston, Texas · Offices in principal cities tedly convenient aspects of microelectronics technology could be avoided and even omitted as nonessential or of considerably lesser importance.

Nick Holonyak, Jr.

Department of Electrical Engineering
University of Illinois
Urbana, Ill.

Sirs:

Professor Anatol Rapoport's review of *The Natural History of Aggression* [Scientific American, October, 1965] makes fascinating, if somewhat solemn, reading. But a Latin usage in the review has gone awry: "...the warmaking state (*Status belligerens?*)"! True, *status* means "state" in Latin—but only the kind of state found in phrases such as "state of mind" or "solid-state physics." In Latin the political state is *civitas*. And *belligero* is a verb of the first conjugation: *belligero, belligerare* and so on. So its present participle is *belligerans,* not *belligerens*. The verb is also very rare. Thus if by "warmaking state" Professor Rapoport meant a state of war, he might better have written *civitas bellum gerens;* if he meant a warlike state, *civitas bellicosa*.

Varian Fry

New York, N.Y.

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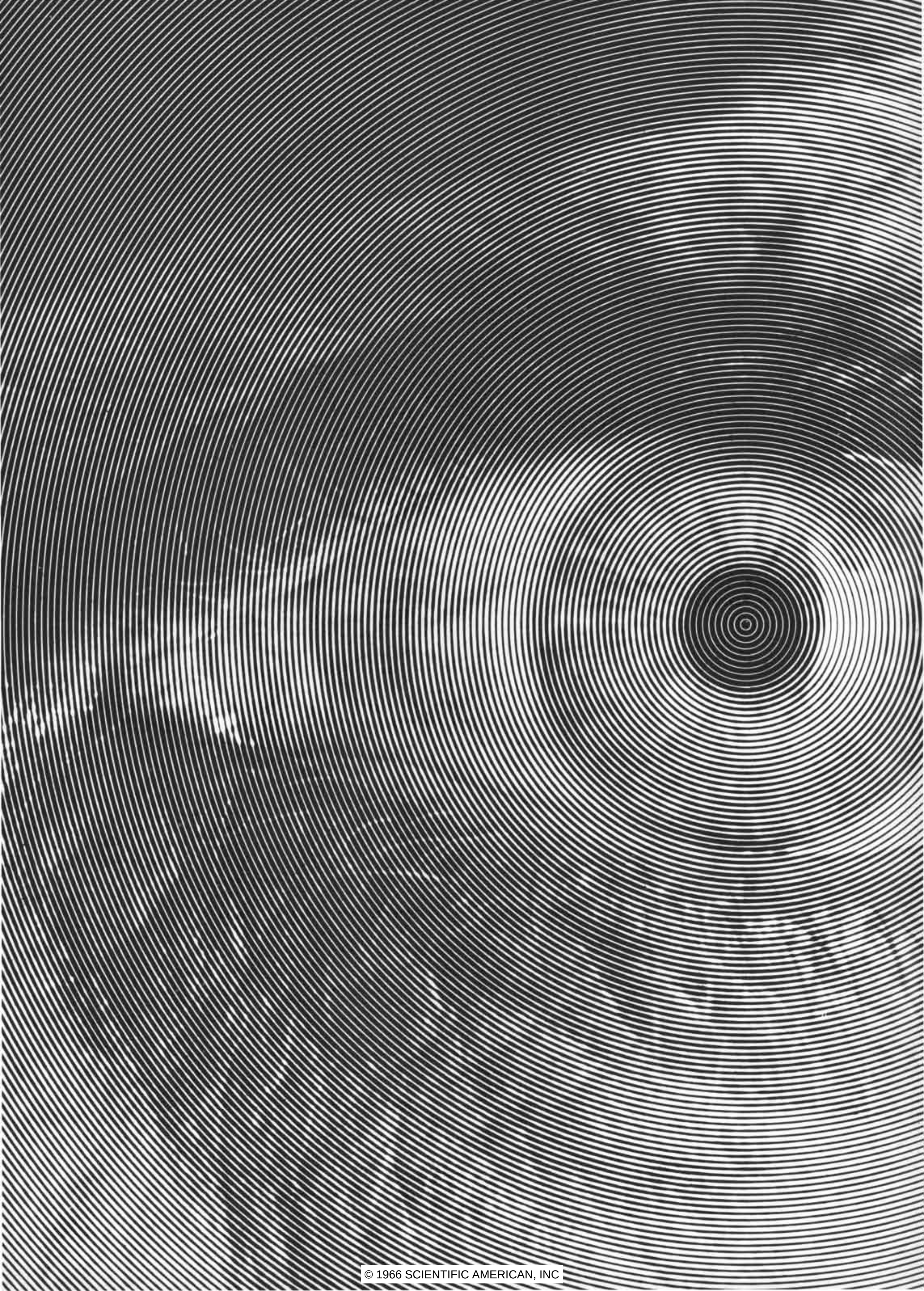
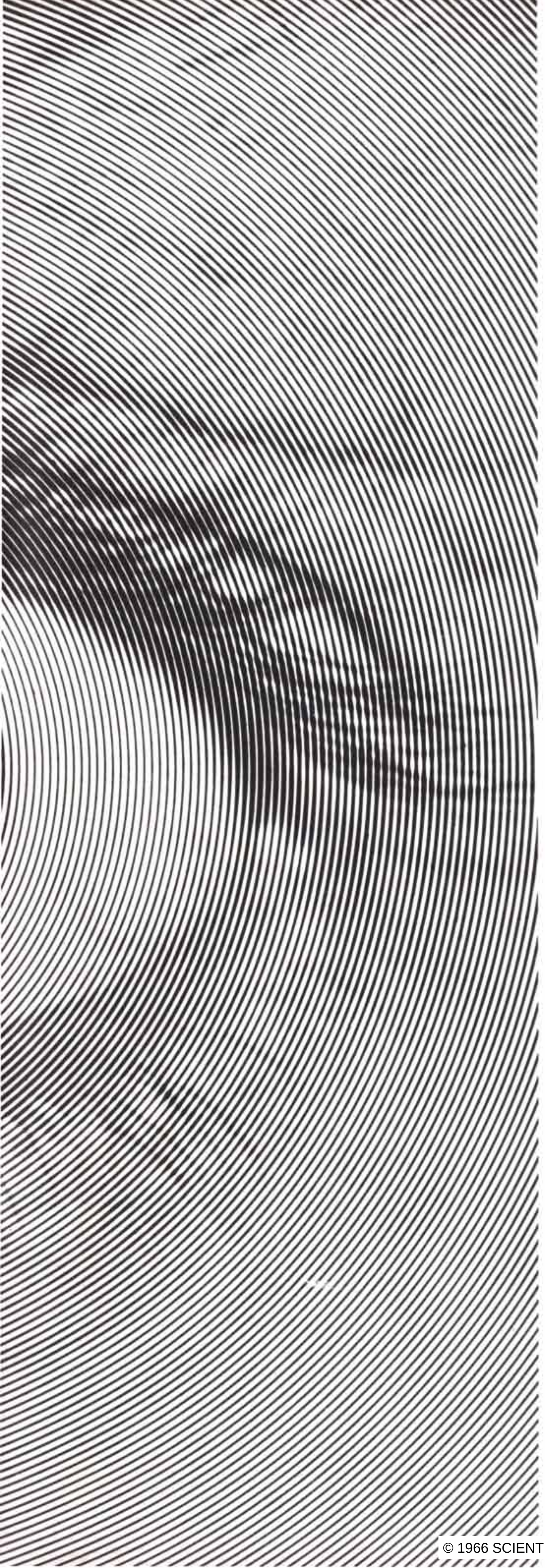




Carats and corneas

What does the world's hardest substance, the diamond, have to do with the world's most sensitive camera, the eye?

Quite a bit. Dr. Lawrence Lewison, a New York optometrist, recently created a plastic contact lens with four tiny grooves around the inside of the rim to permit passage of tears and air.

These lenses are as small as one-third of an inch across and weigh approximately 1/750th of an ounce.

Because of the rugged nature of the plastic and the necessity for absolute accuracy in shaping and smoothing the lens, diamond cutting and polishing tools were found to do the job most economically. (Tungsten carbide cutters dulled in a few hours. A ¾-carat diamond tool, on the other hand, requires sharpening only about every 30 days. Its life expectancy is greater than one year.)

Men of keen vision are using natural and synthetic diamond tools for a variety of jobs in optics, metalworking, and road-building.

Don't be frightened by the cost of diamond tools. Because if you cut, sharpen or smooth *anything* in your business, you can use diamonds profitably. Your tool and wheel manufacturer can show you how. Or write to this magazine for more information.

De Beers

World's leading source
of natural *and* synthetic diamonds
for industry . . . backed by
the Diamond Research Laboratory

Shannon, Ireland

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

FEBRUARY, 1916: "Another opposition of Mars has taken place, and if history repeats itself, the Sunday supplements should be telling us just what horsepower is ordinarily required to operate a Martian pumping-station, what kind of harvesting machinery the Martians use in gathering their crops and how a self-confessed 'scientist' in Podunk proposes to telegraph to our neighbors on the ruddy planet. Our one hope in the present instance of escaping these periodic lucubrations is the possibility that martial affairs on earth may successfully vie in interest with Martian affairs elsewhere. The question of the habitability of Mars is one to which some of our gravest astronomers have not scorned to direct their attention. A wordy battle has indeed been waged on this subject for a generation, and it has been fought with scientific weapons. Nothing has been proved. The 'canals' are still exactly as debatable as they were when their existence was first proclaimed by Schiaparelli nearly 40 years ago. While on the one hand Professor Lowell and his associates continue to draw certain surface-markings as geometrical spider-lines, we behold a committee of the British Astronomical Association publishing (no longer ago than last summer) an emphatic announcement that the evidence afforded by the last favorable opposition of Mars proves all such geometrical markings, including the 'double' canals, to be mere optical illusions."

"In the *Proceedings* of the National Academy of Sciences, Theodore Lyman of Harvard University describes his experiments with a vacuum spectroscope containing a concave grating arranged so that the path of the light from its source to the photographic plate is wholly in rarefied gas. In the earlier experiments with a strong disruptive discharge in hydrogen at two or three millimeters' pressure the spectrum was extended to a wave-length of 900 angstrom units. In later experiments with helium free from nitrogen the limit was extended to wave-length 600. Three hydrogen lines, predicted by Ritz on theoretical grounds, were found at 1,216, 1,026 and 972. With pure hydrogen they are best seen with a disruptive discharge, but an alternating discharge of 60 cycles per second produces them in helium containing that trace of hydrogen so difficult to remove. The disruptive discharge is required to produce the seven or eight new helium lines with wave-lengths shorter than 900. The limit now reached is set by the adjustment and dimensions of the apparatus, and Lyman sees no insuperable difficulty in further extension. A considerable region remains for exploration between 600 and one angstrom unit, which is the wave-length of X-rays, as determined by the Braggs."

"The late Dr. Aksel Steen, director of the Norwegian meteorological service, had charge of working up the magnetic observations made by Amundsen on his northwest passage of some years ago. *Terrestrial Magnetism* publishes a letter written by Dr. Steen shortly before his death last May, stating that two or three years more would be required to complete the work. The writer declares that it will be impossible to give a definite position for the north magnetic pole, because in his opinion this pole 'is not a fixed point attached to a certain geographical latitude and longitude but must be defined as that point on the surface of the earth where the horizontal intensity at the moment is zero.' The discussion of Amundsen's observations will probably show that the pole has a mean daily and yearly periodic motion, together with more or less irregular displacements."

Scientific American.

FEBRUARY, 1866: "We have in previous numbers of our paper fully described the simple and beautiful process of Mr. Woodbury of England by which photographic pictures may be transferred to metallic plates and then printed—in much the same way that copper-plate engravings are produced. We have lately had the pleasure of receiving from the editor of the London *Photographic News* a specimen of this new art of printing, which in its details of light and shadow, softness and artistic finish is all that could be desired. The new process is exceedingly simple, and there is hardly any limit to its application. It is admirably adapted to book illustrations and for many purposes will supersede wood and plate engravings. Natural objects can be photographed and then reproduced upon metallic plates for printing with a fidelity and harmony in the gradation of tints which hand work cannot possibly imitate."

"The ooze from the bottom of the Atlantic has been described by Mr. Sidebotham in a paper read before the Manchester Philosophical Association. In the unsuccessful attempts made to raise the Atlantic cable the grapnels and hooks brought up with them a quantity of ooze, some of which was scraped off and preserved. He obtained specimens of the deposit from Mr. Fairbairn and submitted them to microscopic examination. In appearance the deposit resembles dirty clay and reminds one of the chalk of Dover; indeed, it presents such appearances as would lead to the inference that a bed of chalk is now being formed at the bottom of the Atlantic. It was composed entirely of minute organisms, which exhibited a very fragmentary condition."

"At the last sitting of the French Academy of Sciences, M. Leon Foucault produced a new apparatus for regulating electric light. It keeps two charcoal rods at the required distance by means of an automatic motion, which pushes them forward or draws them back, as occasion requires. The two sets of clockwork which produce this effect communicate with an electro-magnet, which, as it bends either to the right or the left, puts the corresponding set in motion and, when in an intermediate position, stops the motion of both. In order to establish a connection between the two sets, so that the one may not be independent of the other, M. Foucault has introduced a sun-and-planet wheel, which acts on the catch of the electro-magnet."

"The great Cincinnati bridge about to be suspended across the Ohio River will be the longest in the world, being more than 2,000 feet longer than the suspension bridge over the Niagara River and 540 feet longer than the Menai Bridge in England. Its total span will be 1,057 yards. The massive stone piers tower 110 feet over the floor of the bridge and 200 feet above their foundations."

Here's why it was possible for millions to witness the Gemini 7/6 recoveries as they happened, live, hundreds of miles at sea.

Coverage of the Gemini 6 and 7 astronauts' successful return to Earth marked a historic TV "first"—live action televised far out at sea. The events were beamed instantly to millions of North Americans and Europeans.

Eyewitness news like this was made possible by ITT's transportable satellite-communication earth station. Located aboard the Navy aircraft carrier *U.S.S. Wasp,* the station transmitted microwave signals from TV cameras on the carrier via the Comsat Early Bird satellite and ground station at Andover, Maine.

From Andover, the signals were simultaneously distributed via microwave to the U.S. TV networks' facilities and retransmitted via Early Bird to ground stations in Europe.

ITT's transportable earth station opens new horizons in communications. Now virtually any event on earth may be televised internationally as it happens, wherever it happens.

The earth station was designed, built and installed by ITT Federal Laboratories. It was operated aboard the *U.S.S. Wasp* by ITT World Communications Inc., the international communications subsidiary of ITT.

Today there are nine ITT earth stations around the world. All have performed successfully in a variety of satellite-communication tests using Telstar, and NASA's Relay and Syncom.

Helping people and nations communicate—that's a vital part of ITT's business.

ITT

International Telephone and Telegraph Corporation, New York, N.Y.

THE AUTHORS

NOEL DE NEVERS ("Tar Sands and Oil Shales") became interested in the subject of his article while he was working on processes for the secondary recovery of petroleum, a matter he discussed in an article in SCIENTIFIC AMERICAN last July. His additional technical interests include problems in fluid mechanics. De Nevers, who was graduated from Stanford University and obtained a Ph.D. at the University of Michigan, is assistant professor of chemical engineering at the University of Utah. He went there after a period in which he worked on secondary recovery processes at the Chevron Research Corporation, a subsidiary of the Standard Oil Company of California.

ROBERT W. HOLLEY ("The Nucleotide Sequence of a Nucleic Acid") is professor of biochemistry and chairman of the section of biochemistry and molecular biology of the division of biological sciences at Cornell University. He was graduated from the University of Illinois in 1942 and obtained a Ph.D. at Cornell in 1947. He joined the Cornell faculty in 1948, and during his years there he has also worked with the U.S. Plant, Soil and Nutrition Laboratory at the university. Holley and his colleagues spent four years isolating one gram of pure transfer ribonucleic acid and three more years ascertaining its chemical structure. Holley received the 1965 Albert D. Lasker award for basic medical research for the work described in his article.

FREDERICK REINES and J. P. F. SELLSCHOP ("Neutrinos from the Atmosphere and Beyond") are respectively professors of physics at the Case Institute of Technology and the University of the Witwatersrand. Reines is also head of the department of physics at the Case Institute. He is a graduate of the Stevens Institute of Technology and obtained a doctor's degree at New York University. As a member of the staff at the Los Alamos Scientific Laboratory for 15 years before going to Case in 1959, he participated in the test of the first atomic bomb and the first thermonuclear device. Sellschop, who is a native of South Africa, obtained a bachelor's degree at the University of Pretoria, a master's degree at the University of Stellenbosch and a Ph.D. at the University of Cambridge. His collaboration with Reines in the field of neutrino physics began in 1962, when he visited the Case Institute. Sellschop writes that in such spare time as he has he likes "to grow roses, listen to lieder and try to understand events in Africa from their paleontological beginnings to the present day."

JULIUS H. COMROE, JR. ("The Lung"), is professor of physiology and director of the Cardiovascular Research Institute at the San Francisco Medical Center of the University of California. He went to the institute in 1957 after 21 years as a member of the faculty at the Graduate School of Medicine of the University of Pennsylvania. Earlier he had received undergraduate and medical degrees from that university. Comroe is involved as writer, editor or consultant in many activities related to his professional interests. He was president of the American Physiological Society in 1960–1961.

PETER R. SWANN ("Stress-Corrosion Failure") works in the United States Steel Corporation's Edgar C. Bain Laboratory for Fundamental Research. He was born in Britain and obtained a degree in metallurgy at the University of Wales in 1956. "I went to Canada," he writes, "to study new processes for winning metals from their ores" but "was diverted from this intention by a talented professor at the University of Alberta and spent a year with him on the development of titanium alloys." With an interest in research thus "firmly established," he obtained a Ph.D. at the University of Cambridge and also "married a Swedish girl who had come to Cambridge to study the English language." In 1960, "attracted by the comparatively warmer reception, higher salary and better working conditions offered by American employers," he moved to the U.S. and took up his current work. "My main research interest at present is in developing and improving techniques for examining reactions occurring at or near metal surfaces. I relax by skiing in the winter and flying in the summer."

DAVID JENSEN ("The Hagfish") works in the division of marine biology at the Scripps Institution of Oceanography of the University of California at San Diego, where he is an Established Investigator of the American Heart Association. Jensen received bachelor's, master's and doctor's degrees in physiology from the University of California at Berkeley. He has spent 10 years in cardiac research and nine years studying the hagfish, an animal to which he turned because he thought it might prove useful for basic research on cardiac physiology. "Subsequent events seem to have vindicated this opinion," he writes. He is working also "on the electrophysiology of cardiac automatism in several species of animal."

EDWARD R. LaCHAPELLE ("The Control of Snow Avalanches") is senior scientist in the department of atmospheric sciences of the University of Washington and avalanche-hazard forecaster in the Forest Service of the U.S. Department of Agriculture. "I am more or less leading a double career in glaciology and avalanche science," he writes. "These have a common ground in snow physics, which I consider to be my primary specialty." LaChapelle, a native of Tacoma, Wash., was graduated from the University of Puget Sound in Tacoma in 1949 and forthwith began his investigations of snow physics. His work for the Forest Service includes the preparation of training films. The most recent of them, "Avalanche Control," has had wide international distribution.

D. D. KOSAMBI ("Scientific Numismatics") is an Indian mathematician and historian with a broad spectrum of interests. After receiving his education in India and at Harvard University, from which he was graduated summa cum laude in the class of 1927, he began his career in mathematics, working first on aspects of geometry and then on probability. He became interested in numismatics when he turned to coinage problems "to see if I had mastered statistical methods." Some of the coins Kosambi describes in the present article "had to be associated with a king or kings," and that led him to a study of early Indian history. "The sources were so poor," he writes, "that I had to learn Sanskrit and edit some of them myself." He has written two books as a result of his historical researches: *An Introduction to the Study of Indian History* and *The Culture and Civilisation of Ancient India in Historical Outline*. He has also edited some works of poetry, including the oldest known anthology of classical Sanskrit verse.

STEPHEN TOULMIN, who in this issue reviews *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science*, by Carl G. Hempel, is professor of ideas and philosophy at Brandeis University.

Keeping Alive in Space: A report from General Dynamics

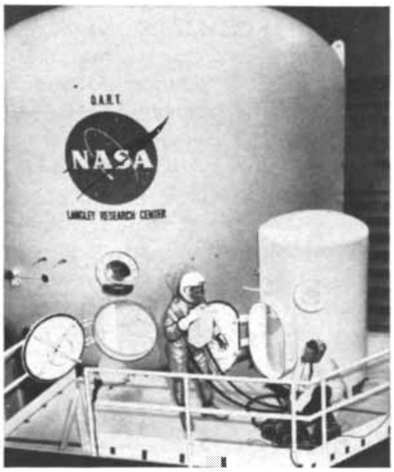
QUESTION: An astronaut in space needs 11 pounds of water and two pounds of oxygen a day to live. If you seal him into a spaceship, how long could just 11 pounds of water and two pounds of oxygen last him?

ANSWER: Forever, if necessary.

The reason, of course, is that air and water can be regenerated indefinitely, providing that a total man-machine system is properly organized.

Such a system is the heart of an experimental life-support facility which General Dynamics has recently built for the National Aeronautics and Space Administration. It is designed to take care of the basic physiological requirements of four men in a zero-gravity environment for a full year, with minimal resupply once every three months.

Regeneration is a basic fact of nature —nothing is ever really lost. The job is done by the total biosphere of the earth, its billions of cubic miles of atmosphere, its millions of miles of earth and sea, its thousands of species of animals, plants, insects and bacteria.



This sealable structure contains the prototype of a life-support system which includes facilities to maintain four men in space for a year.

Compressing even part of that system to meet the requirements of men in space is a capability that has developed only recently.

The problem–weight:

General Dynamics has been involved in the requirements of space travel for almost a generation through its development of the Atlas and Centaur space vehicles. We've been working even longer with the problem of sealed environments in the submarines we've been building since 1900.

But the submarine problem is somewhat different. Drinking water and oxygen can be produced directly from the surrounding water—which, because of its buoyancy, also makes weight a relatively minor problem.

In space, weight, including supplies, comes at an incredibly high premium.

Thirteen pounds of water and oxygen per man per day for four men for 365 days adds up to almost ten tons of water and oxygen.

One manned space platform now in development will weigh approximately 25,000 pounds. Without regeneration another 20,000 pounds of just water and air would be needed.

New water from old:

To avoid carrying such excess weight, the system General Dynamics put together for the National Aeronautics and Space Administration ties water, air and waste removal requirements into one integrated system.

Exhaled carbon dioxide, humidity, air contaminants, used washing water and urine are filtered, absorbed, heated, cooled, catalyzed and electrolyzed in a constantly operating process to create pure water and pure oxygen for reuse.

For water recovery in our system, we chose an evaporative method as the most efficient.

Excess vapor from the cabin air, used wash water and urine are collected in holding tanks and are drawn into wicks by capillary action. At the other end of the wick, water is evaporated into a stream of warmed air. The contaminants are left behind in the replaceable wicks. Condensed vapor moves through a series of filters finally to return to a central reservoir as pure water.

Regenerating air:

Air regeneration presents a more complicated problem.

Normal air is a mixture of oxygen, nitrogen, carbon dioxide, water vapor, trace gases and contaminants. Exhaled air contains less oxygen and is enriched with carbon dioxide. On earth the constant interchange between animals, atmosphere and plants consumes the carbon dioxide and the contaminants and supplies fresh oxygen.

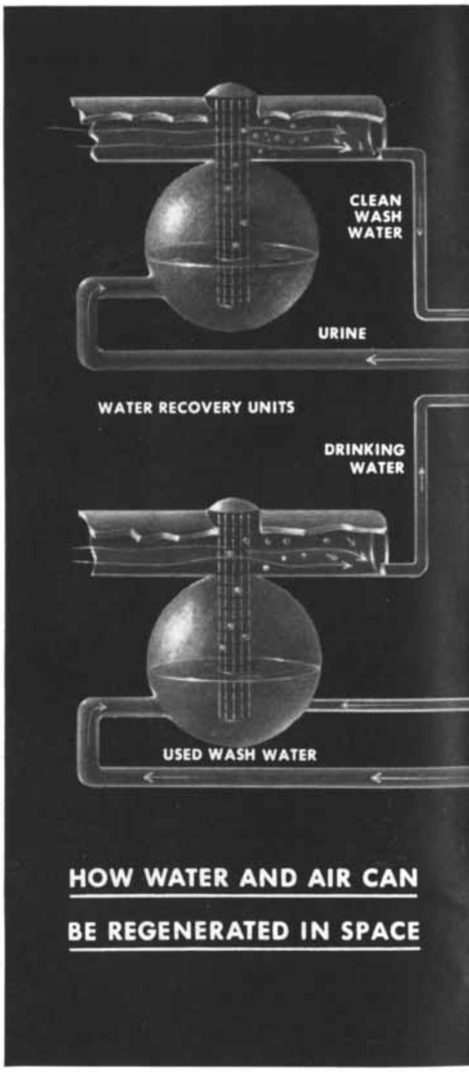
In a sealed ship the oxygen would be rapidly used up and the carbon dioxide built to a poisonous concentration.

Moreover, new contaminants are constantly being formed. At the end of some Project Mercury flights, the cabin air filter contained dozens of contaminants not present at takeoff. Some, such as ammonia, can come from ordinary chemical reactions to an astronaut's own perspiration.

Machinery now has to do the job otherwise done by nature.

How it works:

In our "spaceship," cabin air—the original mixture, plus exhaled breath, excess moisture from cooling systems and new contaminants—is continually circulated through a bank of equipment. A *dehumidifier* removes excess moisture. A



charcoal filter holds back some contaminants. A *catalytic burner* converts others. And a *separator* screens out the carbon dioxide. But the removal isn't final.

The water wrung out by the dehumidifier, for instance, is added to the central tanks for reuse. The carbon dioxide is moved to another chamber where it is mixed with hydrogen at a high temperature in the presence of a catalyst. That reaction creates water and pure carbon.

Techniques have not yet been developed to use the carbon, so it is simply blown into a storage area. But the water, collected through a porous plate, is transferred to an electrolytic cell where an electric current breaks it into hydrogen and oxygen.

The hydrogen is pumped back to fuel the previous reaction in which the water was formed. The oxygen returns to the cabin air to be breathed again.

A separate problem is presented by solid wastes. In a biological food system utilizing algae or bacteria, these wastes might fuel the growth process, but now there is no use for them. International agreements forbid the contamination of space, so they cannot be jettisoned.

Solid wastes, therefore, are dehydrated into a powdery dry residue and stored. In operating spaceships, this may serve as additional shielding against radiation or meteorites.

The work ahead:

The entire life-support system is the most advanced yet developed and does include, of course, much more than the air and water regeneration loop.

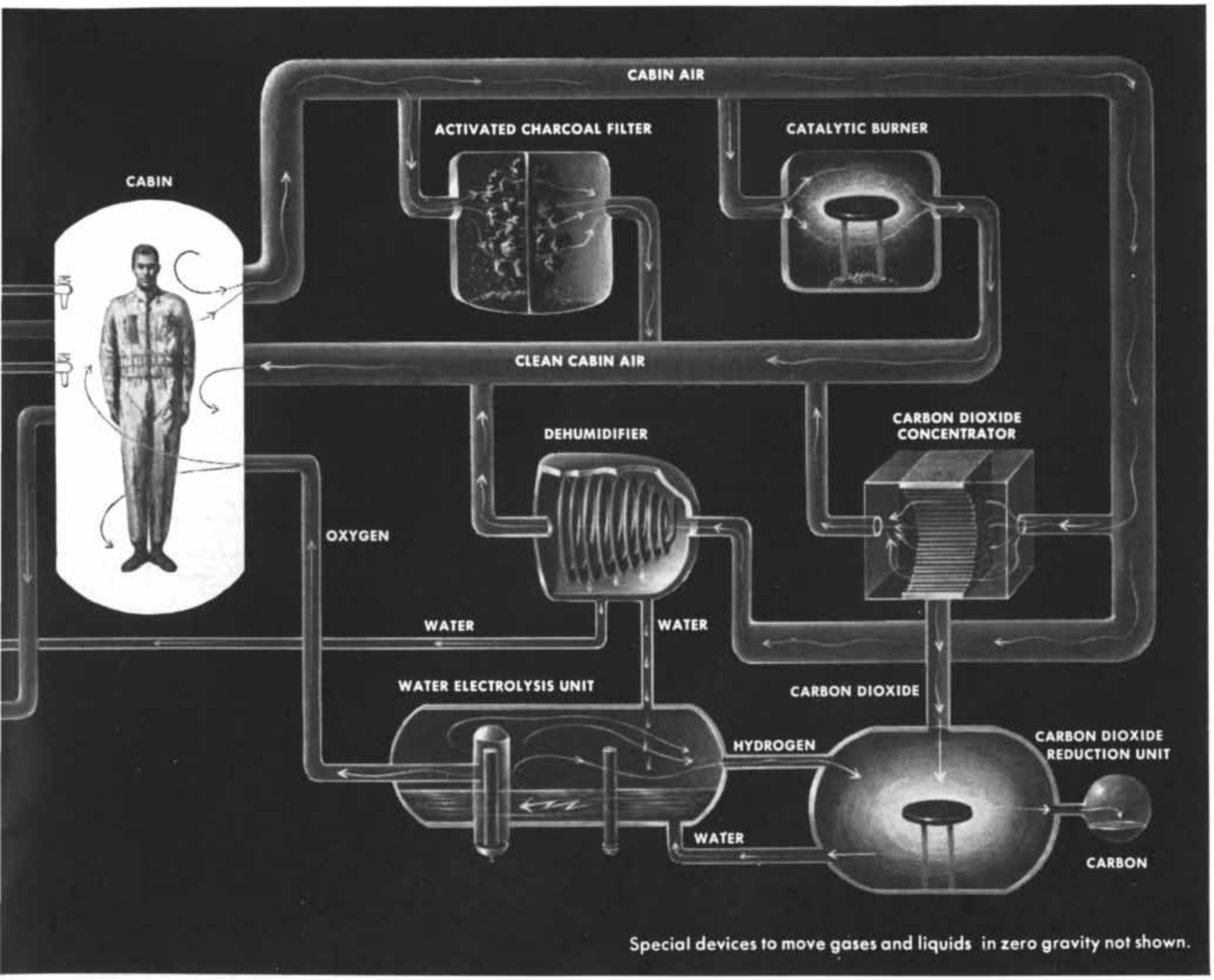
Other facets are an electricity-generating system, mechanisms to circulate gases and liquids, monitoring and control instrumentation, food preparation, storage and other facilities.

Efficient regeneration of food is not yet feasible. So dehydrated food will be carried by the spaceship and resupplied.

All in all, we think the prototype is close to what will be needed in space. But as experimental equipment it's still somewhat heavy—over two tons altogether. We expect the long period of ground testing to be conducted by the National Aeronautics and Space Administration to provide further guidelines for the design of much more compact and lighter equipment.

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

GENERAL DYNAMICS



Special devices to move gases and liquids in zero gravity not shown.

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

How we compressed a year into two minutes

In the creative synthesis of ideas, an end product frequently becomes the point of departure for a fruitful new train of thought. Such was the case when one of our research chemists set out to unriddle the mechanisms of corrosion on chromium plated trim . . . and wound up with a new accelerated corrosion test 1000 times faster than CASS, a widely used standard we helped develop years ago.

Actually, CASS (copper modified acetic acid salt spray) provided just the tool we needed to demonstrate that corrosion on nickel-chromium plating is a cathodically limited electrochemical process. A paper describing this work won the American Electroplaters' Society's award for ". . . the best contribution to the knowledge and art of chromium plating during the year 1961-1962."*

Then a new thought: Could the reaction be accelerated by somehow overcoming the cathodic limitation? As it turned out, we got around the limitation completely by devising a test that required only the anodic reaction at the specimen surface. The resulting electrolytic corrosion test gives nickel-chromium plating the equivalent of a year's service exposure in just *two minutes*.

Such tests have led to major improvements in the service life of automotive trim . . . another example of the way research in depth leads to a better way.

*R. L. Saur, "Toward Protective-Decorative Chromium Plating," *Plating*, Vol. 48 (Dec. 1961) 1310-1319.

General Motors Research Laboratories
Warren, Michigan 48090

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Tar Sands and Oil Shales

The world's largest potential liquid-hydrocarbon reserves are not recoverable by ordinary oil-producing methods. The pace of their exploitation depends on technical, economic and political factors

by Noel de Nevers

The advance of technology exerts a powerful force on the course of events in an industrial society, but it rarely operates alone. More often its effects are interwoven with economics and public policy. This interplay is nowhere more apparent than in the broad field of energy production; here the introduction and exploitation of a new technology is profoundly affected, on the one hand, by governmental considerations of national security, foreign exchange, taxes and conservation and, on the other, by the economic pressures of competition from alternate sources and methods, transport and marketing. The interrelation of these varied factors is illustrated clearly by the current situation involving two unconventional sources of petroleum: the Athabasca tar sands of northern Alberta in Canada and the Green River oil shales of Colorado, Utah and Wyoming.

The two deposits differ in their chemistry, physical state and history. Both, however, contain hydrocarbons that can be converted economically into petroleum products. Both occur at or near the surface, within reach of mining or shallow drilling. And both deposits are of staggering size, even compared with the world's total liquid-fuel reserves [*see upper illustration on page* 27]. Each contains potential petroleum products worth at least hundreds of billions of dollars and possibly trillions of dollars. The big questions, in both cases, are just when, how and by whom these vast reserves are to be exploited. In Canada the issue of the tar sands has recently passed through a controversial phase and is now quiescent; in the U.S. the issue of the oil shales is approaching a time of decision and perhaps of political controversy.

The Athabasca deposit is a bed of bituminous sand—in effect a mixture of sand and paving asphalt—that covers thousands of square miles in northern Alberta. The black sand contains between 12 and 17 percent of oil by weight and the deposits are as much as 200 feet thick. The geologic history of the tar sands is still a debated subject; the general opinion is that the oil flowed into the sands after having been formed by the decomposition of marine organisms in deeper strata. Unlike deep oil formations, which are warm and under high pressure, the tar cannot be produced from wells; at its prevailing temperature of about 36 degrees Fahrenheit it is too stiff to flow.

Two basic approaches have been considered for recovering this asphaltic crude oil. One involves mining the sand and somehow washing the tar from it. The other calls for heating or otherwise treating the tar in place to decrease its viscosity and enable it to flow to wells.

An effective process of the first type was developed some years ago, largely by the Research Council of Alberta, a provincial government agency [see "The Athabaska Tar Sands," by Karl A. Clark; Scientific American, May, 1949]. The mined tar sand is agitated in hot water through which air is bubbled. The bubbles carry oil globules to the surface in a watery froth and the sand grains settle out, along with most of the accompanying clay and silt. The water-laden asphaltic crude-oil froth is dried and then heated in a coking unit that produces coke for in-plant fuel and a cracked distillate that can be refined into a "synthetic" crude oil; this is further refined into the usual petroleum products [*see illustration on page* 25].

The fundamentals of this hot-water system have been known for some time; the barriers to commercial exploitation were the high cost of mining and production, the remoteness of the deposits from potential markets and the expense and difficulty of refining the tar to get a satisfactory yield of end products. Developments in large-scale mining machinery have lowered the cost of getting the sand into processing plants. The opening of conventional oil fields in southern Alberta has established markets and pipelines that tar sand oil can share. New developments in the catalytic treatment of heavy oils with hydrogen have made the refining process more efficient.

All these factors have combined to make the hot-water method appear economically feasible, and Great Canadian Oil Sands, Ltd., is now building a $191-million plant near Fort McMurray in Alberta to produce oil by this method.

The company expects to mine 100,000 tons of tar sand per day, scooping it from a surface vein 50 to 175 feet thick, and process it to recover 45,000 barrels per day of synthetic oil (a barrel is 42 U.S. gallons). The plant is expected to be in commercial production this year.

Ultimately, however, some way must be found to recover the tar directly from the ground as a fluid, because much of the deposit is too deep for economical open-pit mining. A number of schemes have been proposed and some have been tried on a small scale in the field. The most advanced of them is the process developed by the Shell Oil Company, which would treat the tar sands as a shallow oil field suitable for secondary recovery [see "The Secondary Recovery of Petroleum," by Noel de Nevers; SCIENTIFIC AMERICAN, July, 1965]. As it exists in nature the tar is so viscous that ordinary "fluid drive" methods utilizing water or gas to push it will not move it through its sand matrix to the producing wells. The Shell Company would create horizontal fractures at the bottom of the tar sand formation by pumping in water at a pressure high enough to lift the earth the way a hydraulic jack lifts a heavy load. It has demonstrated that in this way it can produce a horizontal fracture across the bottom of the tar sand deposit. Then it would heat the sand by injecting steam into the horizontal fracture. Finally, when the sand and tar were warm enough, it would inject alternate slugs of steam and of hot water containing sodium hydroxide into one set of wells and remove the solution from another set. It has found that the hot sodium hydroxide solution will pick up the previously warmed tar, forming an oil-water emulsion that flows much more easily than the tar itself. This emulsion would be brought to the surface from the collection wells; the tar would be separated and sent to a processing plant and the water and sodium hydroxide would be reused.

This process is similar to the steam-injection secondary-recovery processes now being developed by various oil companies for use in oil fields with very viscous crudes. The main difference is the horizontal fracture that would be required to start the flow. The tar sands

TAR SAND is exposed along a bank of the Athabasca River north of Fort McMurray in Alberta. The stratum of tar sand, about halfway up the bank, is light in color as a result of weathering. The tar is thought to have flowed upward into sand from older formations.

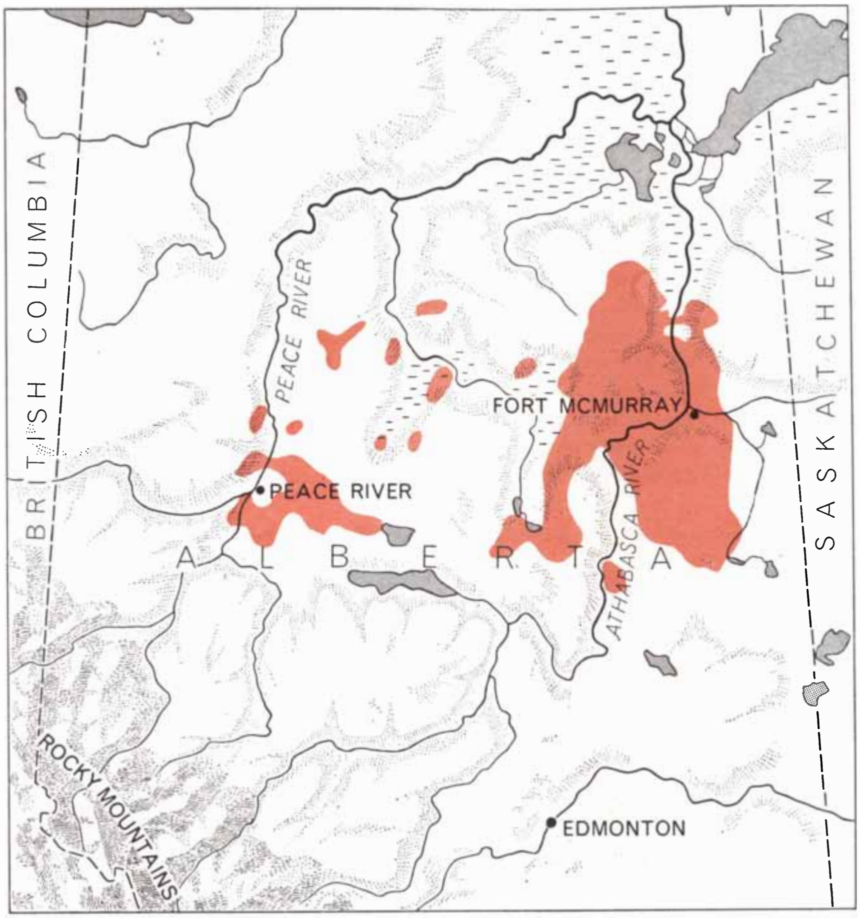
OIL SHALE deposits of the U.S. are concentrated in high plateaus of the Rocky Mountain region. The shale is a finely laminated sedimentary rock, visible in this scene as two pale, steep-faced strata just below the darker layer at the very peak of the mountain.

are shallow compared with typical oil fields, but much closer well spacing would be needed for the fracturing operation; fortunately shallow wells are not expensive to drill, so that the large number of wells per acre in a tar sand project would not cost much more than the smaller number of deeper wells in an oil field.

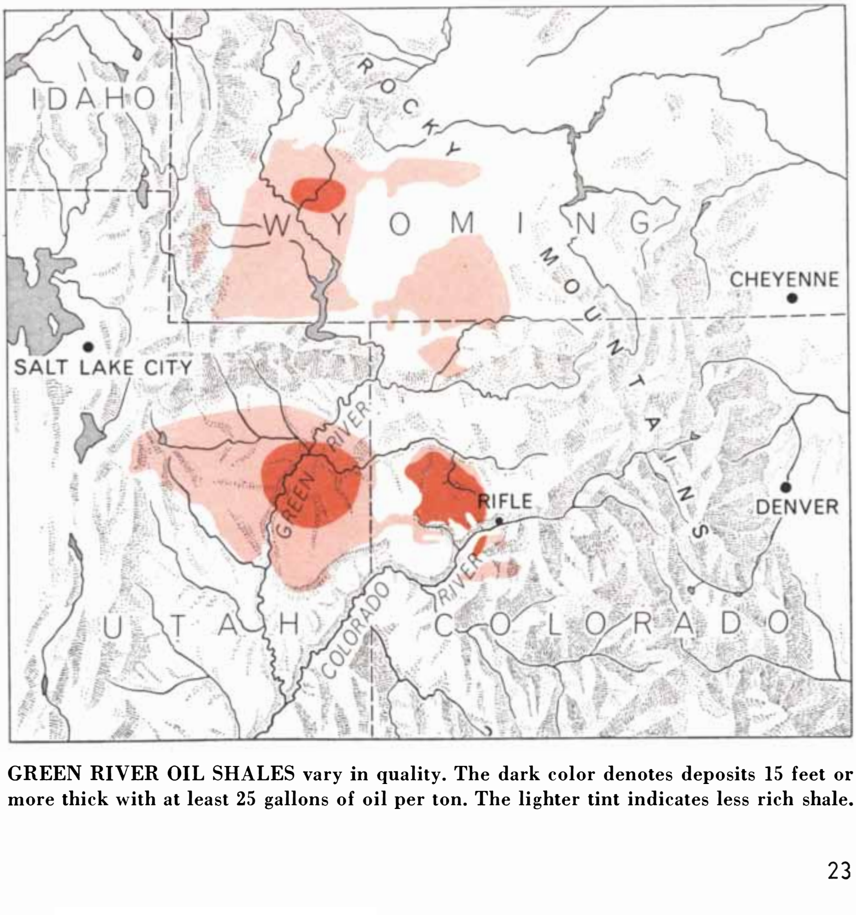
After making a successful small-scale field test of this process, the Shell Company proposed making a larger-scale test provided that the Alberta government would guarantee the company the right to go into commercial production if the trial was successful. This proposal was rejected by the Oil and Gas Conservation Board of Alberta—not on its technical merits but because, like the surface-mining process, it would only be economically feasible if commercial production were carried out on a very large scale. The Shell Company wanted permission to produce 96,000 barrels per day of synthetic crude oil, and the Oil and Gas Board decided that so much extra production would upset the oil market.

A second proposal for recovering the deeply buried tar sands was made by a group of oil companies. They wanted to detonate a small atomic bomb at the bottom of the deposit to fracture and heat a large volume of tar sand. Much of the sand would become warm enough for the oil to become quite fluid, suitable for being pumped out of the heated area with conventional oil-well pumps. This proposal has also been shelved, at least temporarily.

The Athabasca tar sands dwarf all similar deposits. There are, however, significant tar sand deposits in Utah, California and elsewhere, variously called "bituminous sandstones," "asphalt rock," "oil sands" or "sand asphaltum." There is no sharp line of demarcation between a conventional oil field with a very viscous crude oil that will flow into wells and a tar sand with a slightly more viscous crude oil that will not flow into wells in commercial quantities. In the U.S. this has led to legal controversies over oil leases, which normally allow the extraction of oil and gas but not of other minerals. Does an oil lease cover tar sands from which the oil can be recovered only by mining or by some secondary-recovery technique? The Department of the Interior, which supervises oil leases on Government properties, says no. Then how much oil has to be recoverable by simple flow into a well before a "tar sand" becomes a "viscous oil field" and thus comes under the



ATHABASCA TAR SANDS of northern Alberta (*color*) are in a generally undeveloped region of forest and muskeg. There are conventional oil fields in the Edmonton area.



GREEN RIVER OIL SHALES vary in quality. The dark color denotes deposits 15 feet or more thick with at least 25 gallons of oil per ton. The lighter tint indicates less rich shale.

terms of an oil lease? This is still a debated point.

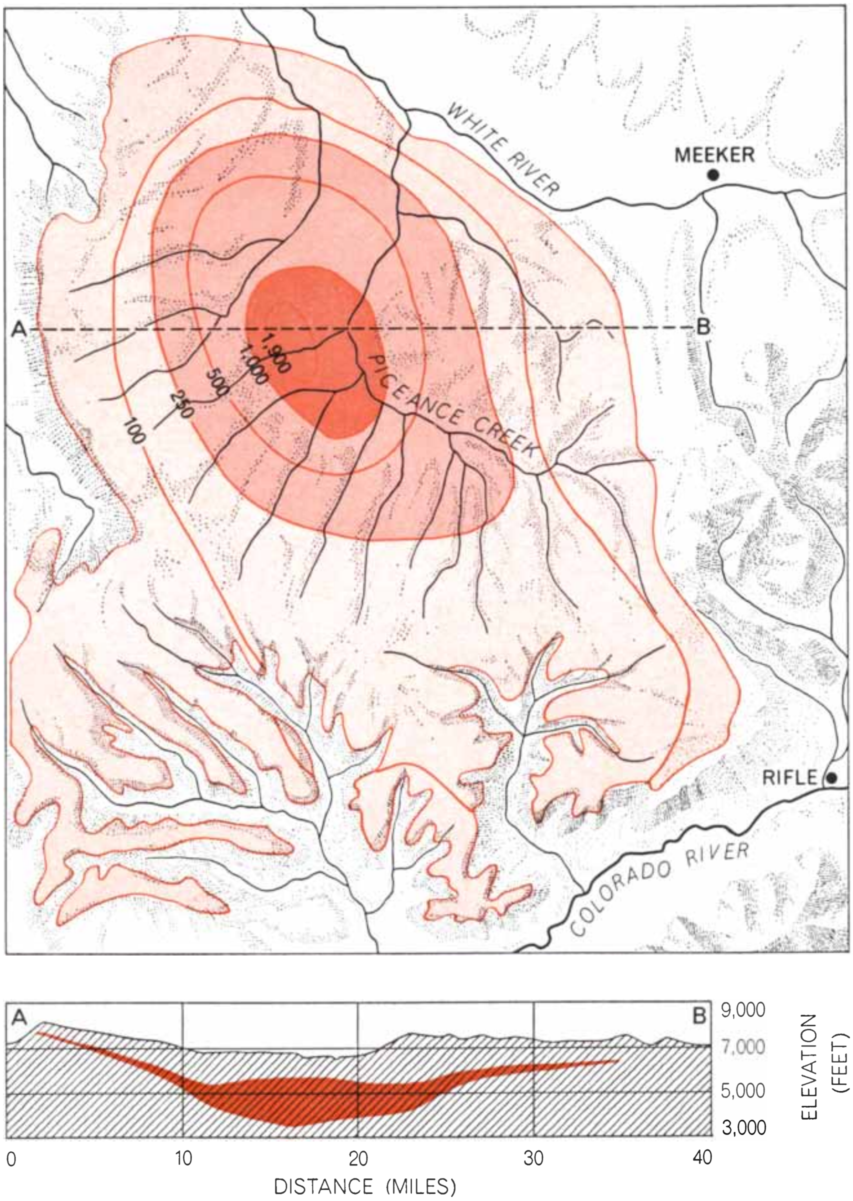
Oil shales are far more widely distributed in the world than tar sands; they occur in many countries and in sedimentary formations of many geologic ages [see "Oil from Shale," by H. M. Thorne; SCIENTIFIC AMERICAN, February, 1952]. In the U.S. there are oil shale beds in at least 30 states. The largest by far is the deposit in the Green River formation of Colorado, Utah and Wyoming. It is the greatest known concentration of hydrocarbons in the world, dwarfing the huge oil pools of the Middle East. The Green River shales—the equivalent of some two trillion barrels of oil, perhaps half of it recoverable by currently known methods—are in effect mountains of oil: some 16,500 square miles of uplifted, eroded sedimentary rock impregnated with organic matter. Actually the rock is not shale and the organic matter is not oil. The Green River rock is a marlstone, a fine-grained, compacted mixture of carbonates, clays and other minerals. The organic matter is not merely a very viscous petroleum like the Canadian tar but a rubbery solid called kerogen, essentially insoluble in petroleum solvents and intimately mixed with the mineral grains.

In terms of chemical structure the difference between petroleum and kerogen is primarily one of geometry. Typical petroleum molecules are linear chains with some rings and branches but little linking between chains. In kerogen, on the other hand, the chains are cross-linked to a significant extent. When kerogen is heated to between 850 and 900 degrees F., the links are broken and the solid undergoes a chemical transformation: a pyrolysis, or thermal cracking, that yields an oil (typically about 66 percent of the kerogen's weight), a fuel gas (9 percent) and a cokelike solid (25 percent). The oil is quite stiff and is high in sulfur and nitrogen content, but after treatment it is as good a feedstock for refining as most good grades of crude oil.

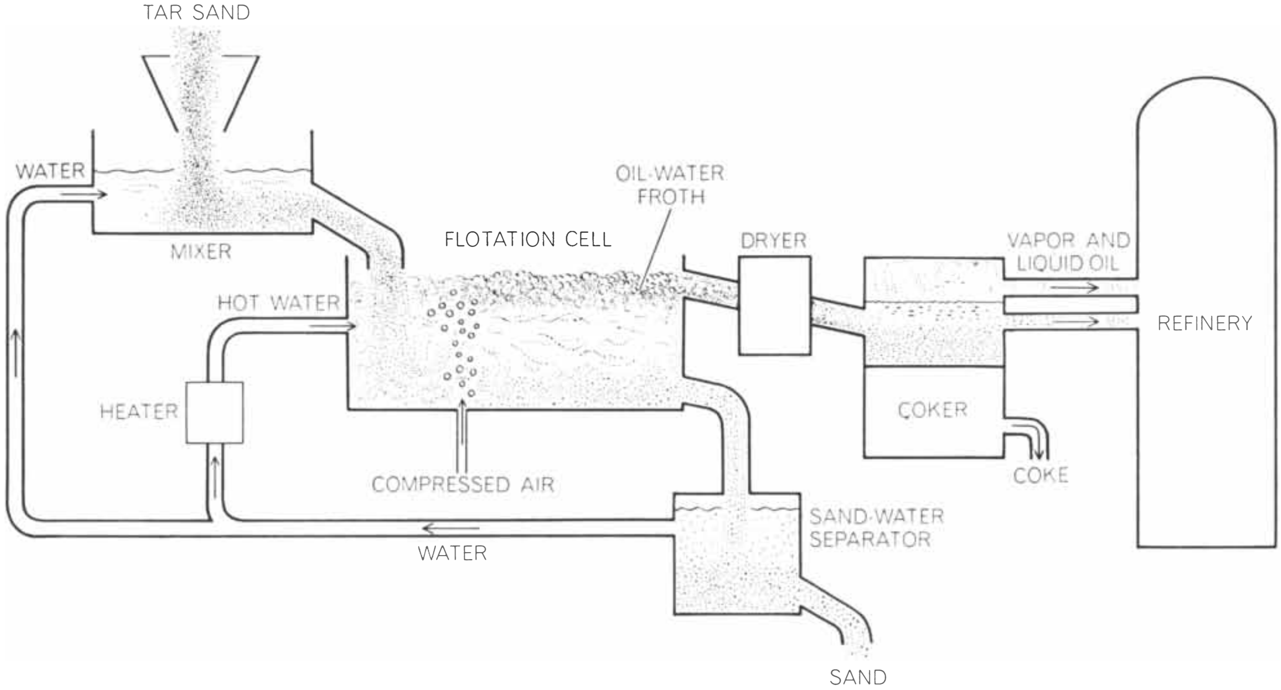
The Green River shales were formed during the Eocene epoch some 50 million years ago by the deposition of silt and organic matter—mostly algae—in large, shallow freshwater lakes. (Petroleum was formed by organic material deposited in oceans.) Today the former lake bottoms have been uplifted to become high plateaus carved by erosion into steep-walled mesas and deep canyons. The richest shale beds are those of the Piceance Creek Basin of northwestern Colorado. Here the layers of shale containing at least 25 gallons of oil per ton range from a few feet to some 2,000 feet in thickness; they are exposed in outcrops on hillsides and canyon walls, but the richest deposits of all are buried under some 1,000 feet of overburden.

Liquid fuels were produced from oil shales as long ago as 1838 in France, and over the years shale has been processed on an industrial scale in several parts of the world, notably Scotland, Estonia, Australia and Manchuria. There was a small shale-oil industry in the U.S. in 1860, but that ended as liquid petroleum became plentiful. Experimental shale projects have been conducted intermittently, however, first by the Bureau of Mines of the Department of the Interior and, with increasing intensity in the past few years, by a number of oil companies.

Like the oil in tar sands, shale oil can be recovered either by mining the shale and then processing it or by heating the kerogen in place. So far attempts to produce shale oil have been largely limited to the first approach: the stone is mined, crushed and then heated in a closed retort to extract the organic material. Experimental work by the Bureau of Mines has established



PICEANCE CREEK BASIN of Colorado has the thickest deposits of rich shale. The contour lines indicate the thickness (*in feet*) of deposits averaging at least 25 gallons of oil per ton. The section (*bottom*) is based on cores taken along the line *AB* on the map.



HOT-WATER PROCESS for washing oil out of tar sand is shown in simplified form. The tar-impregnated sand is mixed with hot water; the slurry flows into an open, water-filled flotation tank in which oil globules attach to air bubbles and rise to form a froth as sand sinks to the bottom. After further separation of water and fine sand in a dryer, the asphaltic crude oil is heated in a coker to produce coke (for use as in-plant fuel) and petroleum fractions to be refined into a "synthetic" crude oil, with sulfur as a by-product.

that, at least in the rich Colorado beds, the shale can be taken from the ground economically by the "room-and-pillar" technique used in some coal and salt mines. A shaft is driven horizontally into an outcrop and the shale is blasted and scooped out of great 120-foot-square "rooms," with 60-foot-square "pillars" left unmined in the center to support the roof. It appears that current mining technology is adequate for getting oil shale out of the ground.

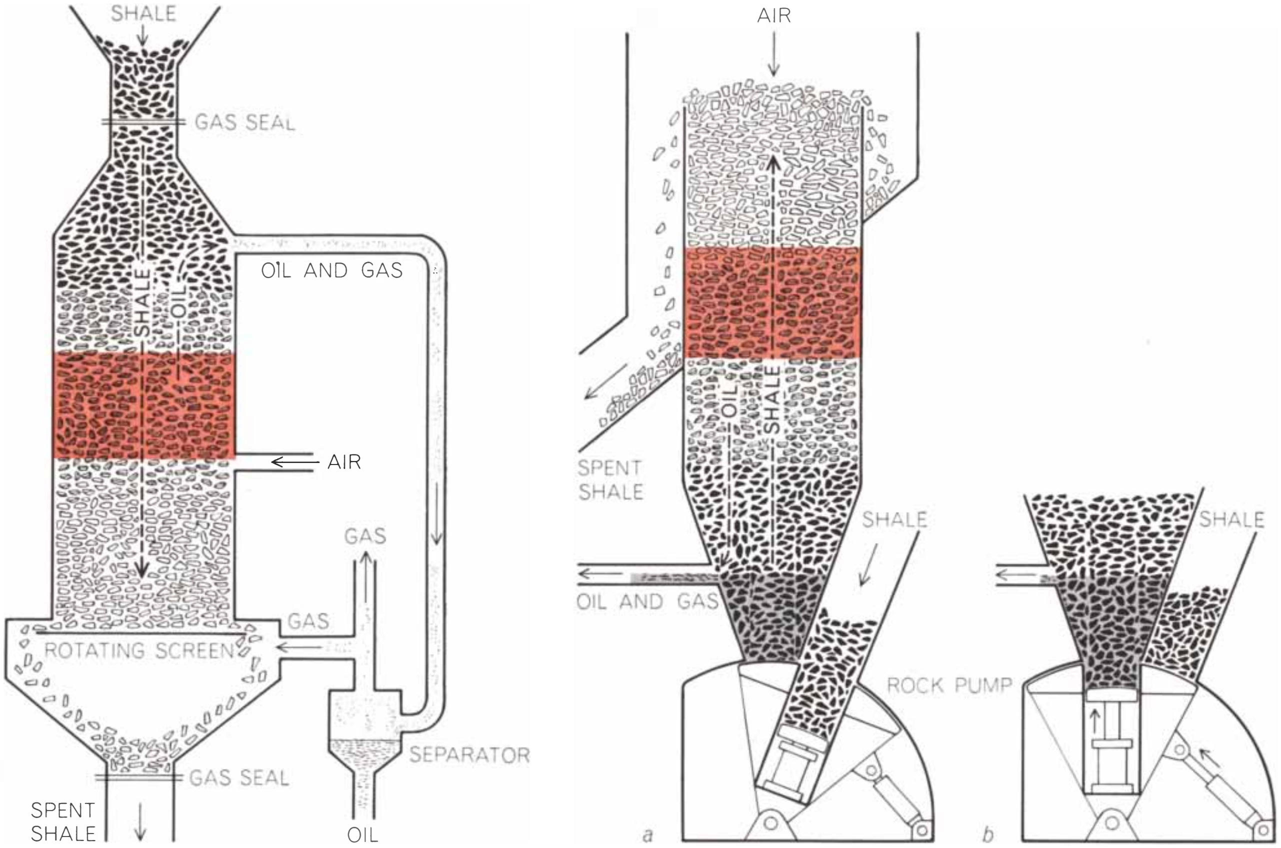
The heating of the shale in retorts, on the other hand, presents many complex problems. A practical retorting process must receive and heat many thousands of tons of raw shale a day and get rid of the "stripped" shale. It must recover all the vaporized oil and condense it to liquid form. It must recover a large part of the heat from the treated shale in order to keep fuel costs down. And it must do all this with a minimum of coolant, since the shale country is extremely poor in water.

The early shale retorts were closed vessels like coke ovens, heated by combustion gases from a furnace outside the retort. The high cost of the fuel they require makes them impractical today. To be economical the retort must obtain its heat by burning the solid coke residue left on the stripped shale or part of the gas produced when the kerogen is heated. This is accomplished in different ways in the three basic retort designs that seem to hold promise for commercial production.

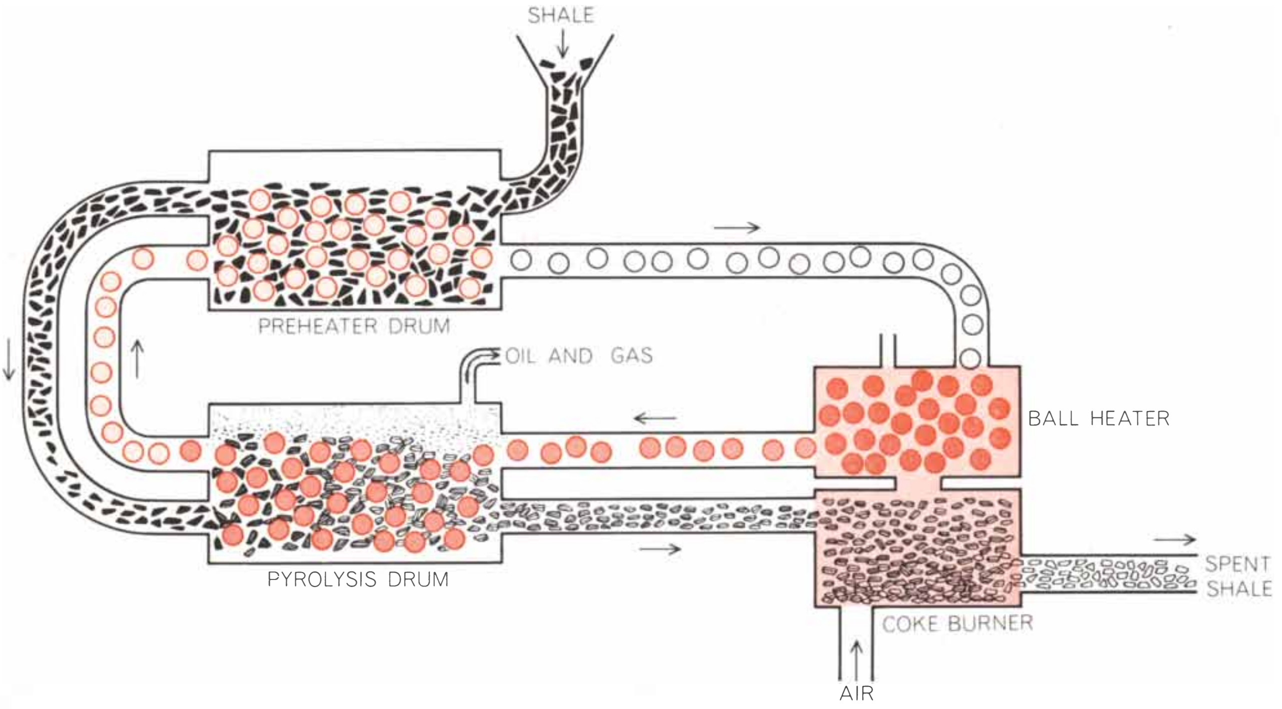
One thermally self-sufficient method is the gas-combustion process developed by the Bureau of Mines at a pilot plant near Rifle, Colo. The crushed shale is introduced at the top of a large retort that resembles a vertical lime kiln or blast furnace. Air and recycled gas from the retorting process move up through the shale, the gas is ignited to provide heat and more heat is derived from the burning of the coke residue. The heat decomposes the kerogen in the shale above the combustion zone [*see drawing at left in top illustration on next page*]. The oil leaves the retort as a mist carried off by the effluent gas. After the oil has been separated part of the gas is recirculated into the retort, where it cools the stripped shale and is itself heated to near combustion temperature. In 1964 the former Bureau of Mines facility was leased to the Colorado School of Mines Research Foundation, which is developing the gas-combustion process further in a joint research effort with a number of oil companies. The group expects to be ready for commercial production within five years.

One difficulty in the gas-combustion process is that the product oil has to move upward out of the retort. The effluent gases must be kept quite warm in order to prevent the oil from condensing and dripping down into the combustion zone, and the oil droplets must be condensed and separated outside the retort. To avoid these requirements the Union Oil Company of California developed a retort in which the shale moves up and hot gas (from the burning of the spent shale's coke residue) is pulled downward by blowers. The gas gives up its heat to decompose the kerogen and is cooled enough by the incoming cold shale so that the oil condenses, drips to the bottom of the retort and is collected as a liquid. This provides better efficiency in heat recovery than the gas-combustion retort and saves the cost of an external oil condenser. The critical design element in this process is a "rock pump" that loads the shale and rams it up through the retort [*see drawing at right in top illustration on next page*]. The Union Oil Company operated a pilot plant in Colorado, testing room-and-pillar mining methods as well as retorting and refining processes, between 1955 and 1958.

Both internally fired retort processes decompose the shale in the presence of air. This reduces yield because it allows



TWO SHALE RETORTS in which heat is generated internally are shown schematically. In the Bureau of Mines process (*left*) the crushed shale moves downward. It is decomposed above the combustion zone (*color*) by heat from the burning of both recycled shale gas and coke on the spent shale. In the Union Oil Company process (*right*) the shale moves upward. Hot gas from the burning coke is drawn down to decompose the shale. A "rock pump" feeds the retort, taking a load of shale (*a*) and ramming it upward (*b*).



HOT-BALL PROCESS developed by the Oil Shale Corporation separates the combustion stage and the decomposition stage. In the version diagrammed countercurrents of shale and hot ceramic balls are tossed together in rotating drums, where the shale is pulverized and decomposed. The coke left on the shale is subsequently burned to bring the ceramic balls back to retorting heat.

some valuable constituents to be burned up, and it also leads to some undesirable chemical reactions between the product oil and the air. Combustion and decomposition are separated in a process developed by the Oil Shale Corporation. The crushed shale is fed into a rotating horizontal kiln along with ceramic balls that have been heated to 1,200 degrees F. As the kiln turns, the balls pulverize the shale and heat it, decomposing the kerogen and driving off the oil as a vapor [*see bottom illustration on opposite page*]. Both the retorted shale and the cooled ceramic balls leave the drum, whereupon the residual coke on the shale can be burned to provide the heat that brings the balls back to retorting temperature. The Oil Shale Corporation has joined the Standard Oil Company of Ohio and the Cleveland Cliffs Iron Company to form the Colony Development Company, which is operating a "semiworks" plant based on the ceramic-ball process and which expects to go into commercial shale-oil production in 1967.

In all the mining-retorting schemes the cost of mining the shale, crushing it and transporting it to the processing plant is three or four times higher than the cost of retorting. The preliminary steps could all be eliminated if some way could be found to retort the shale in the ground. The underground-combustion process widely used in the secondary recovery of petroleum seems to be the only feasible method. In this process several holes would be drilled into a shale formation and air would be pumped down alternate holes. The shale would be ignited at these injection holes and the combustion front would be directed toward recovery wells by the continued injection of compressed air. The hot combustion gases would decompose the kerogen adjacent to the burning zone, and the resulting shale oil and gas would be driven to the recovery wells. The high flow resistance of the fine shale matrix in which the kerogen is dispersed makes in-place retorting extremely difficult, and tests to date have been quite discouraging. Nevertheless, the Sinclair Oil Corporation and others are continuing research on such techniques.

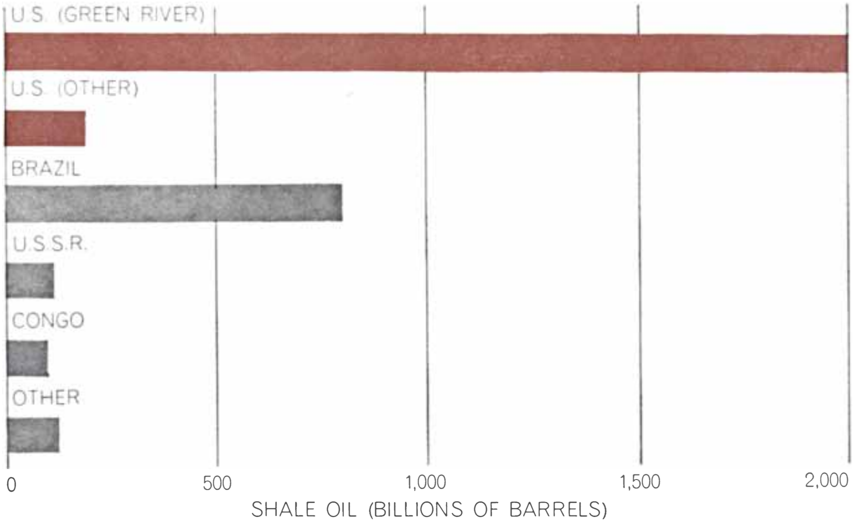
There have been proposals that the high flow resistance of the shale could be overcome through the use of nuclear explosives. A nuclear device small enough to be lowered into a buried shale deposit could be detonated to fracture the rock in place and might break up the shale into fine enough pieces to allow efficient underground-combustion recovery. There are a number of questions that must be answered before a field test can even be considered, but if all the imponderables in a nuclear-explosion technique can be worked out, it might result in very economical production of shale oil.

An in-place retorting process, in addition to saving money, would relieve the producer of a serious waste-disposal problem. A plant producing 50,000 barrels of oil per day would have to dispose of 70,000 cubic yards of spent shale every day—a pile three feet wide, three feet high and 40 miles long! Bureau of Mines tests indicate that after a few years of weathering the waste shale could support vegetation, but the problem of where to put it all would still be formidable. In principle, at least, most of the spent shale could be put back into the holes from which it had been dug; this would raise costs, however, and the chances are it will not be done.

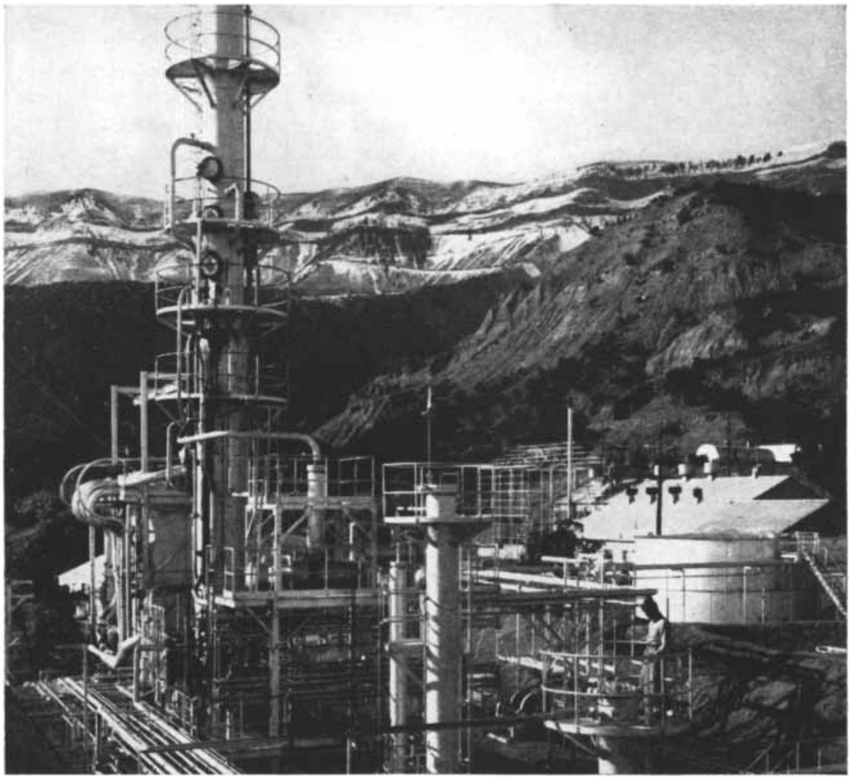
The decision to drill an oil well or start a manufacturing plant is largely a private one, made within the framework of existing laws and economic circumstances. The decision to undertake a tar sand or oil shale project is not so simple. Significant questions of public policy are involved and must be settled through political processes. Moreover, small-scale projects are apparently not economically sound; any tar sand or oil shale operation is going to have to be sizable, producing a minimum of some 50,000 barrels of oil per day. The fact that these unconventional reserves cannot come into the economy gradually—they either come with a bang or not at all—makes the political decisions all the more difficult.

The Athabasca tar sands belong outright to the Alberta provincial government, which owns all subsurface minerals in the province. For many years Alberta's conventional oil fields could have produced more oil than could be marketed at a satisfactory price; the

IMPORTANCE of Athabasca tar and Green River shale reserves is evident if they are compared with known petroleum reserves—the world total and the U.S. (*color*) and Canadian (*dark gray*) shares (*top bar*). All figures are in billions of barrels of oil. Shale-oil estimates vary widely; this one includes shale with more than 15 gallons of oil per ton. Potential reserves of oil made from coal are even greater, but that process is not yet competitive.



DISTRIBUTION of known potential shale-oil reserves is shown by this chart based on U.S. Geological Survey statistics. Here shales assaying 10 or more gallons per ton are included.



REFINERY is part of the shale research center built by the Bureau of Mines at Anvil Points, Colo., and now operated by a research group. Shale is mined from cliffs in background.

government restricted production and was not interested in bringing the tar sands into large-scale oil production. Now the markets have grown. Petroleum supply and demand are in approximate balance and the introduction of moderate amounts of oil from the tar sands will probably not upset the price of oil. Moreover, some experts believe that liquid petroleum production in Alberta is near its peak, since it is becoming increasingly harder to find new oil fields to replace those whose production is beginning to decline. This is a disputed view, but if it is correct, it behooves the government to bring the tar sands into production in order to keep for Alberta its share of the world oil market.

Under these conditions the Alberta government decided to grant licenses to allow production of oil from tar sands up to 5 percent of the total oil production of the province. It was this decision that led to the granting of a production license to Great Canadian Oil Sands and to the refusal of a license—on political and economic grounds—to the Shell Company.

For the Alberta government such issues are resolved into relatively simple yes-or-no decisions on licenses to operate. For the U.S. Government the shaping of policy on oil shale development is more complicated. It requires decisions on the leasing of land, on oil-importation regulations and on taxes.

About 77 percent of the known, commercially exploitable Green River oil shale is on Federally owned land. The other 23 percent is owned by the states or is owned or leased by oil companies. Since 1930 the Federal oil shale lands have been closed to mineral leasing by executive order. The technological advances of the past few years have stimulated increased interest in these lands, and strong pressure is being put on the Department of the Interior to open them up to leasing. Much of the pressure comes from political leaders, chambers of commerce and business groups in the intermountain region. All are anxious to see the oil shales developed as quickly as possible to spur the region's economy. They reason that the oil companies will not spend the millions of dollars required to develop extraction processes unless they own the mineral rights to all the shale. A number of oil companies have pleaded the same case vigorously; others have asked that small leases be granted for research and development. Some independent petroleum engineers and economists support this position.

Others argue the opposite case. They believe that the necessary processes will be developed—are being developed, in fact—whether or not the land is leased, and that after commercial feasibility has been demonstrated the Government will be able to sell mineral leases at much higher prices. Conservationists maintain that the companies' desire to lease is based on their traditional desire to control land, not on any current economic necessity; they point out that some shale land is so rich that one standard 5,120-acre lease tract might contain oil equivalent to 40 percent of the known U.S. petroleum reserves. The conservationists therefore urge the Government to reconsider its standard leasing arrangements and in the meantime to refuse to lease until the oil companies begin to exploit the 23 percent of the shale land to which they now have access.

Shale-oil politics are complicated by the running controversy over oil imports. Petroleum from the Persian Gulf, South America, North Africa and Indonesia can be delivered to U.S. coastal cities at about half the price of domestic oil. The domestic producers of crude oil have succeeded in having laws passed limiting oil imports to about 13 percent of current U.S. consumption. These producers are likely to be as opposed to shale-oil development as they are to crude oil imports.

The attitudes of the diversified oil companies, which refine petroleum products in addition to producing crude, vary with their foreign holdings. The international "have" companies (those owning large reserves of low-cost foreign oil) are generally in no hurry to see shale oil on the market; they would rather bring in their foreign oil. (Many of them own substantial shale reserves and are holding them as a hedge against future developments.) The "have not" companies (diversified producer-refiners without large foreign holdings) are more anxious to develop new sources in the U.S. That is why the Union Oil Company, one of the largest have-nots, developed its shale-oil process. Such companies want assurances that imports will continue to be limited before they will make the capital investments needed to begin shale-oil production.

The question of oil imports affects shale-oil policy even more directly. Each U.S. petroleum refiner receives from a branch of the Department of the Interior an oil-import quota: a permit to bring in a certain quantity of foreign oil at its foreign price. Since this is about half the price of domestic crude, such a permit is equivalent to a cashier's check for half the domestic price of the oil. Import quotas are based on a complicated formula that includes the amount of domestic oil refined by the company. The Department of the Interior could decide that any shale oil refined by a company should or should not be included as domestic oil refined; if it is not, then a refiner who purchases shale oil rather than domestic petroleum will lose part of his import quota. In that case a shale-oil seller would have to offer his product at a price much lower than that of a comparable domestic petroleum to be competitive. Import-quota policy is therefore another administrative lever that could hasten or retard the production of shale oil.

Finally, there are the tax aspects. In order to encourage the search for petroleum, which is a risky business, Congress created the "depletion allowance" that permits a petroleum producer to exempt from Federal income taxation 27½ percent of the value of his crude-oil production. Shale-oil production is similarly encouraged, but according to Internal Revenue Service rulings only by an exemption of 15 percent of the value of the shale as mined and crushed. The Oil Shale Corporation, the Union Oil Company and other companies have argued that both the lower percentage and the fact that it is applied to the rock rather than to the retorted oil are discriminatory; the Union Oil Company has implied that it would have gone into commercial production with its technologically satisfactory process if shale oil had the same tax treatment as crude petroleum.

One branch of the Department of the Interior can encourage or not encourage shale-oil production by leasing or not leasing land; another branch of the department can affect the situation through import-quota policy; the Internal Revenue Service can play a large role by regulating the industry's taxes. Clearly some national goals and ground rules for the shale-oil industry are needed, and a broad Federal policy will have to be enunciated before long.

The tar sands are on their way to commercial development, with a large-scale commercial plant under construction. Shale oil is not far behind; it seems likely that there will be significant production by 1970. In both cases the magnitude of the deposits, their potential value, their possible disruptive effects on existing industries and the resulting political pressures will pose continuing problems for the governments involved.

LAYER OF SAND, about 175 feet thick, to be mined in Alberta is generally buried under less than 150 feet of clay and rock. Here sand is being loaded for a pilot plant; commercial mining will be done by two giant bucket-wheel excavators that can dig 100,000 tons per day.

SHALE DEPOSITS will probably be mined in Colorado by techniques developed by the Bureau of Mines. Large underground "rooms" are mined by drilling, blasting and loading with heavy equipment. The bolts and plates in the roof lessen the likelihood of cave-ins.

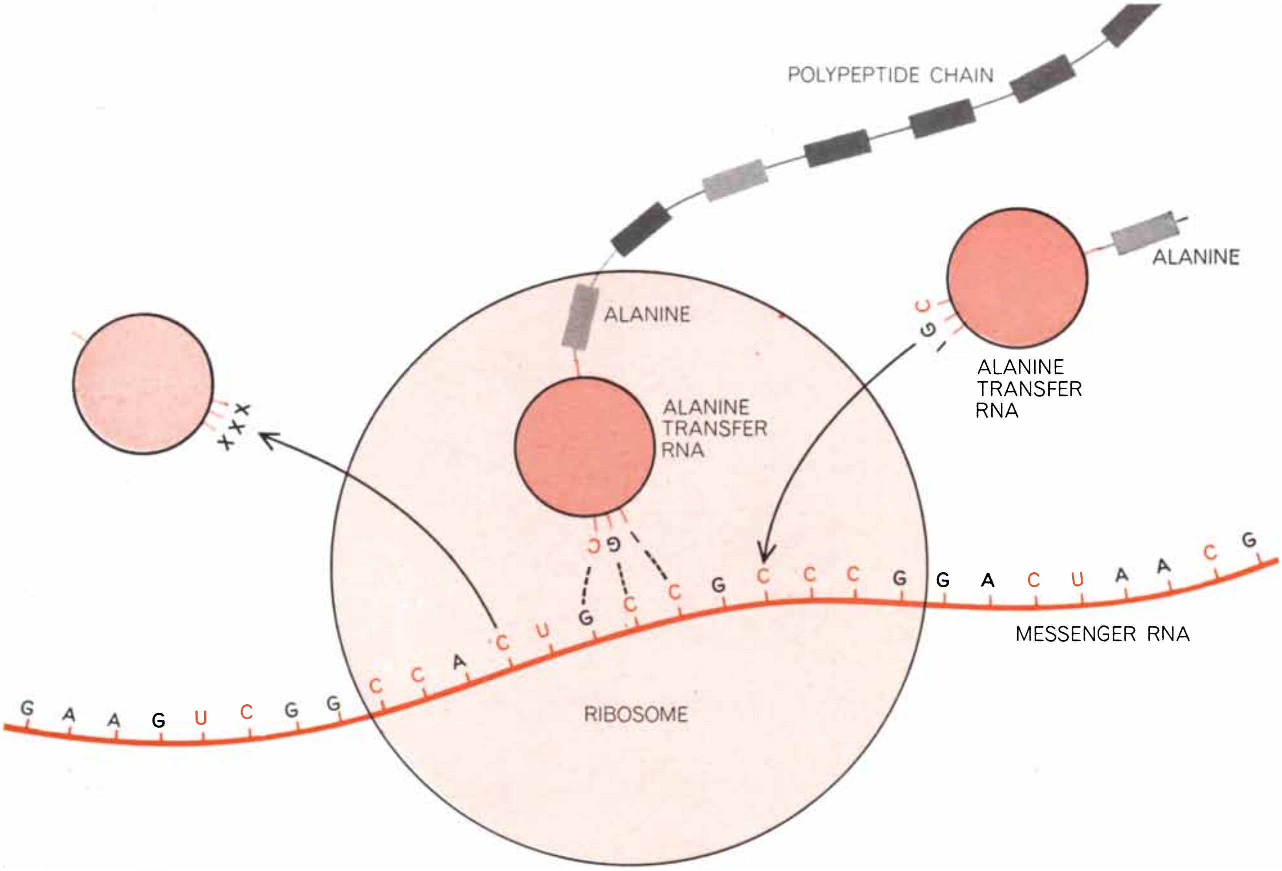
The Nucleotide Sequence of a Nucleic Acid

For the first time the specific order of subunits in one of the giant molecules that participate in the synthesis of protein has been determined. The task took seven years

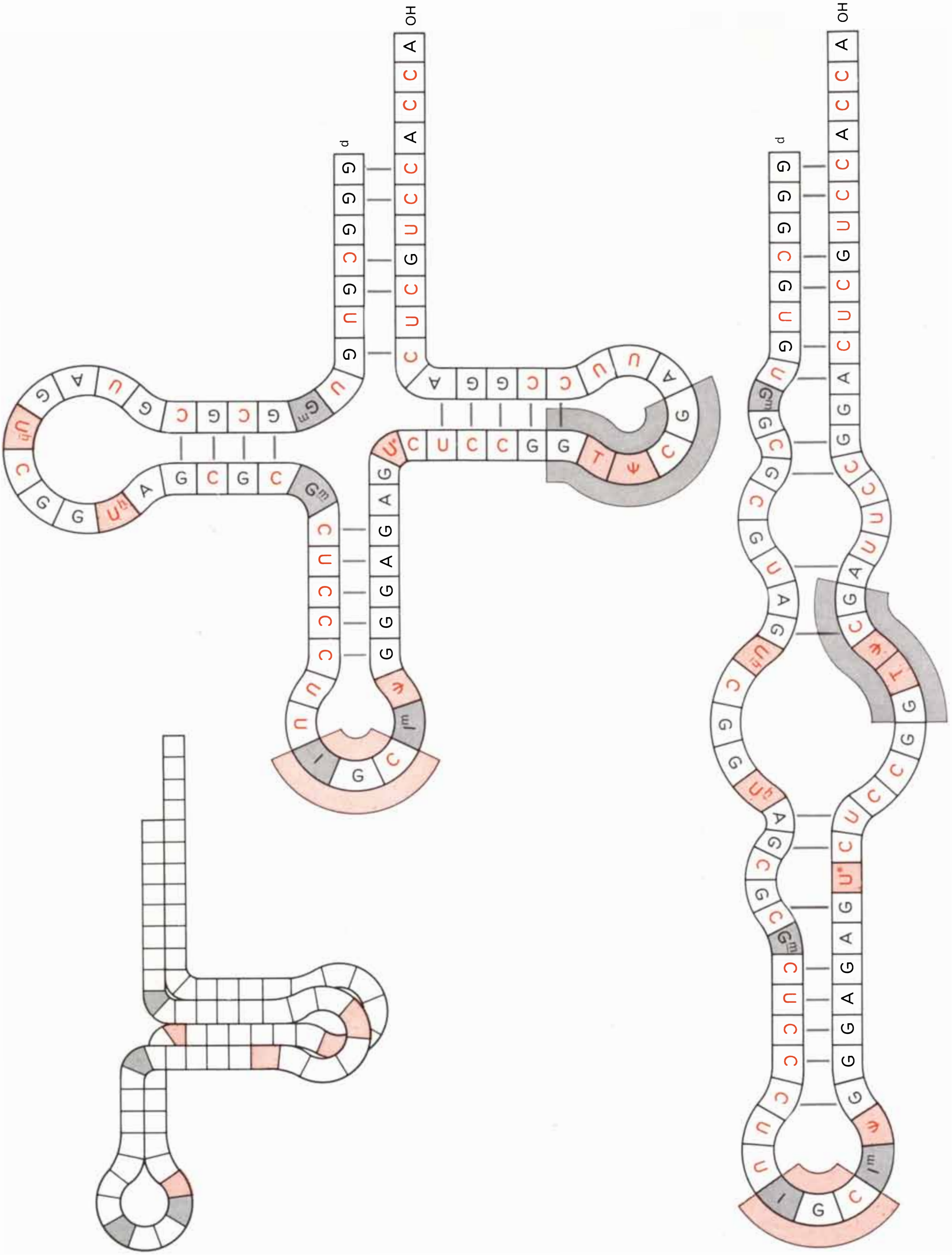
by Robert W. Holley

Two major classes of chainlike molecules underlie the functioning of living organisms: the nucleic acids and the proteins. The former include deoxyribonucleic acid (DNA), which embodies the hereditary message of each organism, and ribonucleic acid (RNA), which helps to translate that message into the thousands of different proteins that activate the living cell. In the past dozen years biochemists have established the complete sequence of amino acid subunits in a number of different proteins. Much less is known about the nucleic acids.

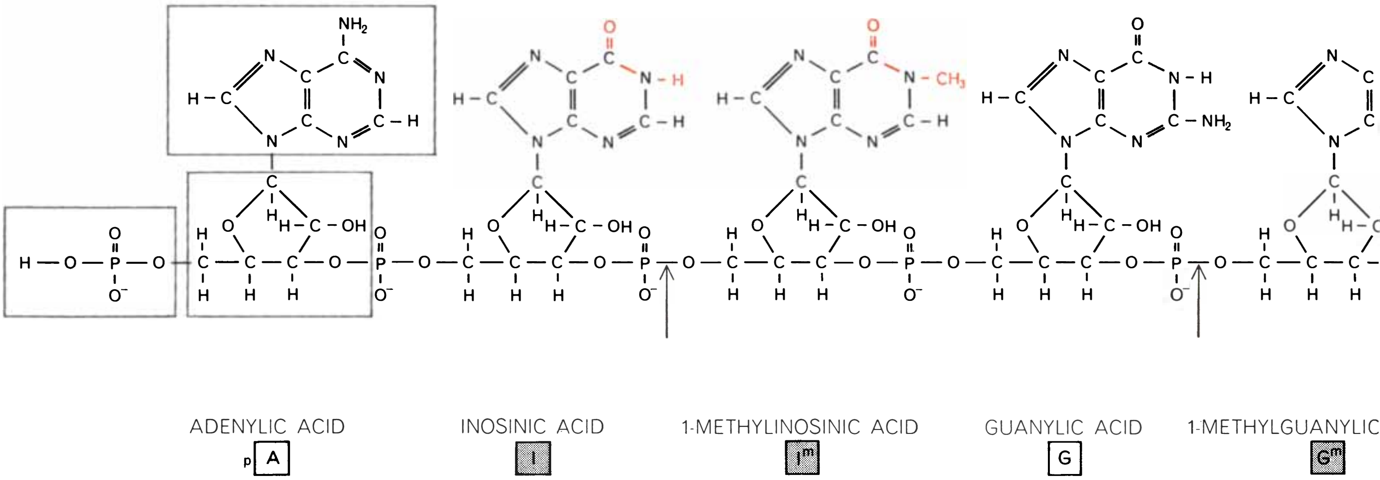
Part of the reason for the slow progress with nucleic acids was the unavailability of pure material for analysis. Another factor was the large size of most nucleic acid molecules, which often contain thousands or even millions of nucleotide subunits. Several years ago, however, a family of small molecules was discovered among the ribonucleic



ROLE OF TRANSFER RNA is to deliver a specific amino acid to the site where "messenger" RNA and a ribosome (which also contains RNA) collaborate in the synthesis of a protein. As it is being synthesized a protein chain is usually described as a polypeptide. Each amino acid in the polypeptide chain is specified by a triplet code, or codon, in the molecular chain of messenger RNA. The diagram shows how an "anticodon" (presumably I—G—C) in alanine transfer RNA may form a temporary bond with the codon for alanine (G—C—C) in the messenger RNA. While so bonded the transfer RNA also holds the polypeptide chain. Each transfer RNA is succeeded by another one, carrying its own amino acid, until the complete message in the messenger RNA has been "read."



HYPOTHETICAL MODELS of alanine transfer ribonucleic acid (RNA) show three of the many ways in which the molecule's linear chain might be folded. The various letters represent nucleotide subunits; their chemical structure is given at the top of the next two pages. In these models it is assumed that certain nucleotides, such as C—G and A—U, will pair off and tend to form short double-strand regions. Such "base-pairing" is a characteristic feature of nucleic acids. The arrangement at the lower left shows how two of the large "leaves" of the "clover leaf" model may be folded together. The triplet I—G—C is the presumed anticodon shown in the illustration on the opposite page. The region containing the sequence G—T—Ψ—C—G may be common to all transfer RNA's.

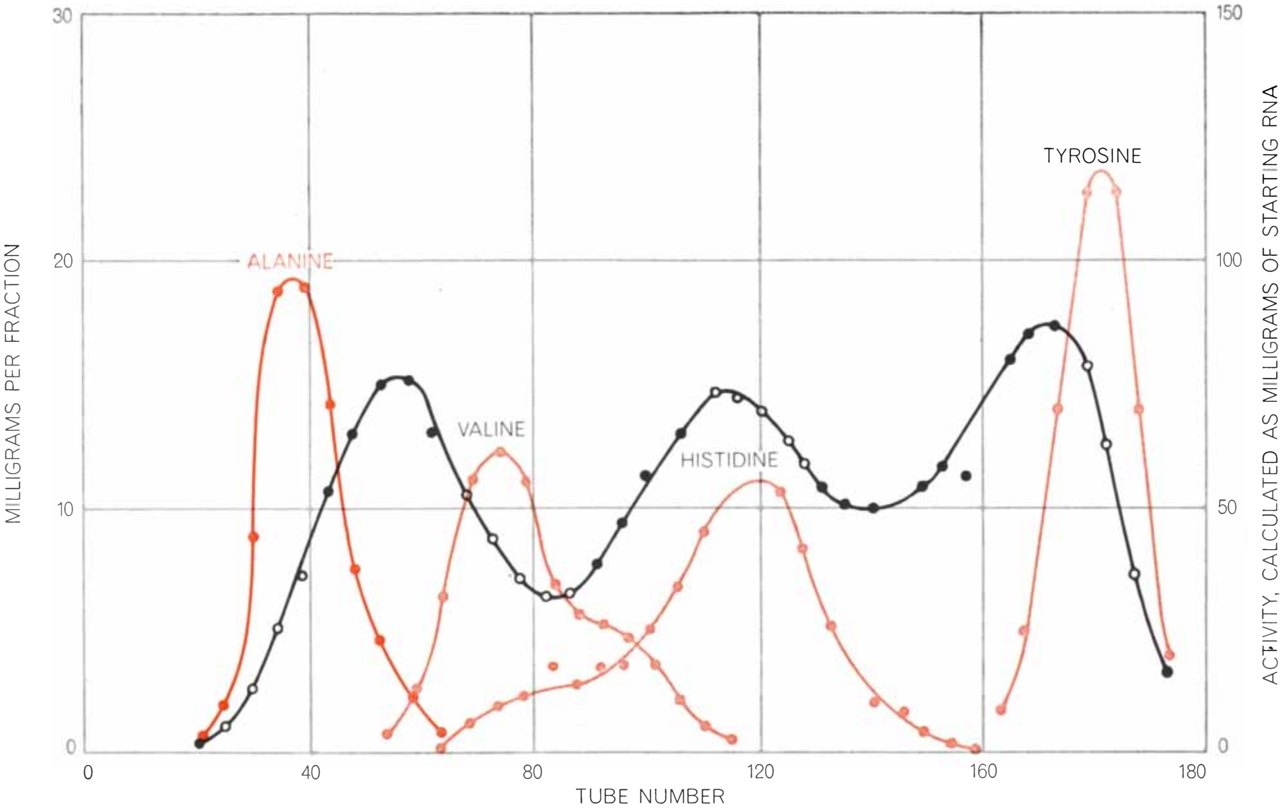


NUCLEOTIDE SUBUNITS found in alanine transfer RNA include the four commonly present in RNA (A, G, C, U), plus seven others that are variations of the standard structures. Ten of these 11 different nucleotide subunits are assembled above as if they were linked together in a single RNA chain. The chain begins at the left with a phosphate group (*outlined by a small rectangle*) and is followed by a ribose sugar group (*large rectangle*); the two groups alternate to form the backbone of the chain. The chain ends at the right with

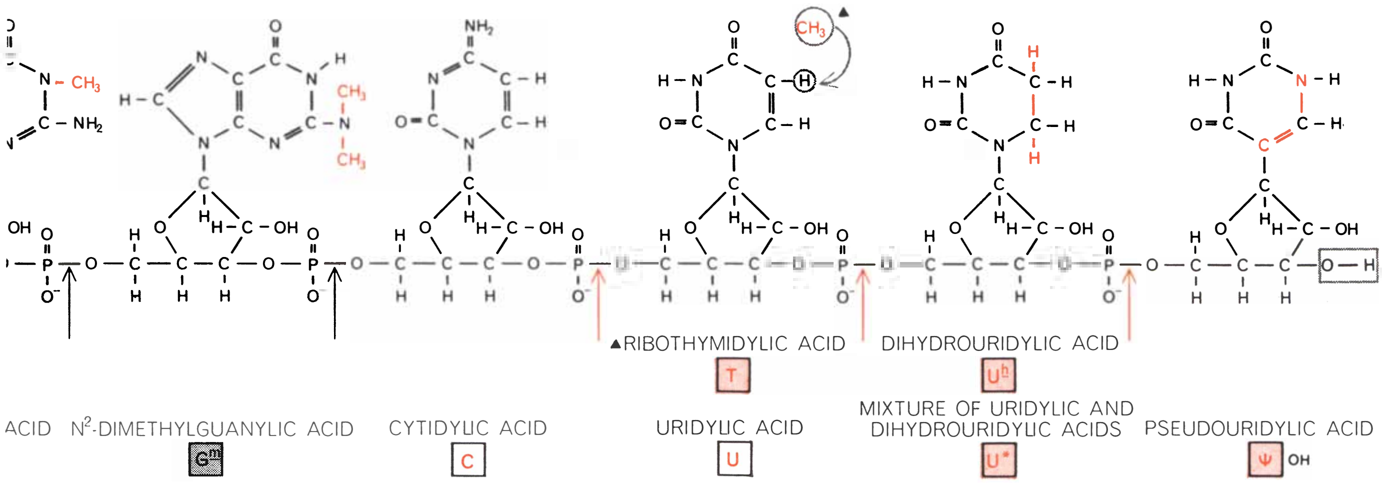
acids. My associates and I at the U.S. Plant, Soil and Nutrition Laboratory and Cornell University set ourselves the task of establishing the nucleotide sequence of one of these smaller RNA molecules—a molecule containing fewer than 100 nucleotide subunits. This work culminated recently in the first determination of the complete nucleotide sequence of a nucleic acid.

The object of our study belongs to a family of 20-odd molecules known as transfer RNA's. Each is capable of recognizing one of the 20 different amino acids and of transferring it to the site where it can be incorporated into a growing polypeptide chain. When such a chain assumes its final configuration, sometimes joining with other chains, it is called a protein.

At each step in the process of protein



COUNTERCURRENT DISTRIBUTION PATTERN shows two steps in the separation of alanine transfer RNA, as carried out in the author's laboratory. After the first step the RNA content in various collection tubes, measured by ultraviolet absorption, follows the black curve. Biological activity, indicated by the amount of a given amino acid incorporated into polypeptide chains, follows the colored curves. Pure transfer RNA's of four types can be obtained by reprocessing the tubes designated by open circles.



a hydroxyl (OH) group. Each nucleotide subunit consists of a phosphate group, a ribose sugar group and a base. The base portion in the nucleotide at the far left, adenylic acid, is outlined by a large rectangle. In the succeeding bases the atomic variations are shown in color. The base structures without color are those commonly found in RNA. Black arrows show where RNA chains can be cleaved by the enzyme takadiastase ribonuclease T1. Colored arrows show where RNA chains can be cleaved by pancreatic ribonuclease.

synthesis a crucial role is played by the structure of the various RNA's. "Messenger" RNA transcribes the genetic message for each protein from its original storage site in DNA. Another kind of RNA—ribosomal RNA—forms part of the structure of the ribosome, which acts as a jig for holding the messenger RNA while the message is transcribed into a polypeptide chain [*see illustration on page 30*]. In view of the various roles played by RNA in protein synthesis, the structure of RNA molecules is of considerable interest and significance.

The particular nucleic acid we chose for study is known as alanine transfer RNA—the RNA that transports the amino acid alanine. It was isolated from commercial baker's yeast by methods I shall describe later. Preliminary analyses indicated that the alanine transfer RNA molecule consisted of a single chain of approximately 80 nucleotide subunits. Each nucleotide, in turn, consists of a ribose sugar, a phosphate group and a distinctive appendage termed a nitrogen base. The ribose sugars and phosphate groups link together to form the backbone of the molecule, from which the various bases protrude [*see illustration at top of these two pages*].

The problem of structural analysis is fundamentally one of identifying each base and determining its place in the sequence. In practice each base is usually isolated in combination with a unit of ribose sugar and a unit of phosphate, which together form a nucleotide. Formally the problem is analogous to determining the sequence of letters in a sentence.

It would be convenient if there were a way to snip off the nucleotides one by one, starting at a known end of the chain and identifying each nucleotide as it appeared. Unfortunately procedures of this kind have such a small yield at each step that their use is limited. The alternative is to break the chain at particular chemical sites with the help of enzymes. This gives rise to small fragments whose nucleotide composition is amenable to analysis. If the chain can be broken up in various ways with different enzymes, one can determine how the fragments overlap and ultimately piece together the entire sequence.

One can visualize how this might work by imagining that the preceding sentence has been written out several times, in a continuous line, on different strips of paper. Imagine that each strip has been cut in a different way. In one case, for example, the first three words "If the chain" and the next three words "can be broken" might appear on separate strips of paper. In another case one might find that "chain" and "can" were together on a single strip. One would immediately conclude that the group of three words ending with "chain" and the group beginning with "can" form a continuous sequence of six words. The concept is simple; putting it into execution takes a little time.

For cleaving the RNA chain we used two principal enzymes: pancreatic ribonuclease and an enzyme called takadiastase ribonuclease T1, which was discovered by the Japanese workers K. Sato-Asano and F. Egami. The first enzyme cleaves the RNA chain immediately to the right of pyrimidine nucleotides, as the molecular structure is conventionally written. Pyrimidine nucleotides are those nucleotides whose bases contain the six-member pyrimidine ring, consisting of four atoms of carbon and two atoms of nitrogen. The two pyrimidines commonly found in RNA are cytosine and uracil. Pancreatic ribonuclease therefore produces fragments that terminate in pyrimidine nucleotides such as cytidylic acid (C) or uridylic acid (U).

The second enzyme, ribonuclease T1, was employed separately to cleave the RNA chain specifically to the right of nucleotides containing a structure of the purine type, such as guanylic acid (G). This provided a set of short fragments distinctively different from those produced by the pancreatic enzyme.

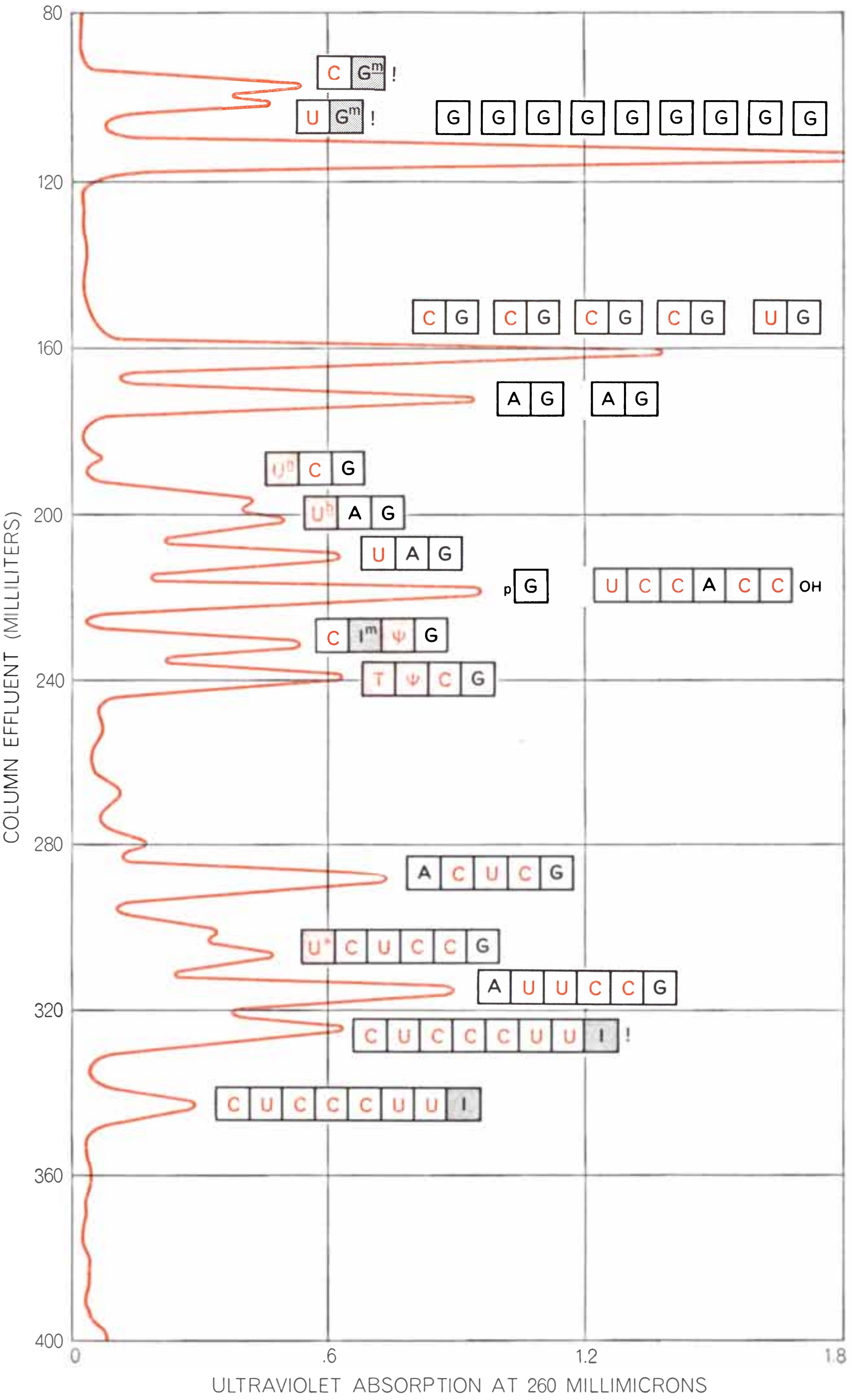
The individual short fragments were isolated by passing them through a thin glass column packed with diethylaminoethyl cellulose—an adaptation of a chromatographic method devised by R. V. Tomlinson and G. M. Tener of the University of British Columbia. In general the short fragments migrate through the column more rapidly than the long fragments, but there are exceptions [*see illustration on next page*]. The conditions most favorable for this separation were developed in our laboratories by Mark Marquisee and Jean Apgar.

The nucleotides in each fragment were released by hydrolyzing the fragment with an alkali. The individual nucleotides could then be identified by paper chromatography, paper electrophoresis and spectrographic analysis.

This procedure was sufficient to establish the sequence of each of the dinucleotides, because the right-hand member of the pair was determined by the particular enzyme that had been used to produce the fragment. To establish the sequence of nucleotides in larger fragments, however, required special techniques.

Methods particularly helpful in the separation and identification of the fragments had been previously described by Vernon M. Ingram of the Massachusetts Institute of Technology, M. Laskowski, Sr., of the Marquette University School of Medicine, K. K. Reddi of Rockefeller University, G. W. Rushizky and Herbert A. Sober of the National Institutes of Health, the Swiss worker M. Staehelin and Tener.

For certain of the largest fragments, methods described in the scientific literature were inadequate and we had to develop new stratagems. One of these involved the use of an enzyme (a phosphodiesterase) obtained from snake venom. This enzyme removes nucleotides one by one from a fragment, leaving a mixture of smaller fragments of all possible intermediate lengths. The mixture can then be separated into fractions of homogeneous length by passing it through a column of diethylaminoethyl cellulose [*see illustration on opposite page*]. A simple method is available for determining the terminal nucleotide at the right end of each fraction of homogeneous length. With this knowledge, and knowing the length of each fragment, one can establish the sequence of nucleotides in the original large fragment.



SEPARATION OF RNA FRAGMENTS is accomplished by chromatography carried out in a long glass column packed with diethylaminoethyl cellulose. The curve shows the separation achieved when the column input is a digest of alanine transfer RNA produced by takadiastase ribonuclease T1, an enzyme that cleaves the RNA into 29 fragments. The exclamation point indicates fragments whose terminal phosphate has a cyclical configuration. Such fragments travel faster than similar fragments that end in a noncyclical phosphate.

A summary of all the nucleotide sequences found in the fragments of transfer RNA produced by pancreatic ribonuclease is shown in Table 1 on page 36. Determination of the structure of the fragments was primarily the work of James T. Madison and Ada Zamir, who were postdoctoral fellows in my laboratory. George A. Everett of the Plant, Soil and Nutrition Laboratory helped us in the identification of the nucleotides.

Much effort was spent in determining the structure of the largest fragments and in identifying unusual nucleotides not heretofore observed in RNA molecules. Two of the most difficult to identify were 1-methylinosinic acid and 5,6-dihydrouridylic acid. (In the illustrations these are symbolized respectively by I^m and U^h.)

Because a free 5′-phosphate group (p) is found at one end of the RNA molecule (the left end as the structure is conventionally written) and a free 3′-hydroxyl group (OH) is found at the other end, it is easy to pick out from Table 1 and Table 2 the two sequences that form the left and right ends of the alanine transfer RNA molecule. The left end has the structure pG—G—G—C— and the right end the structure U—C—C—A—C—COH. (It is known, however, that the active molecule ends in C—C—AOH.)

The presence of unusual nucleotides

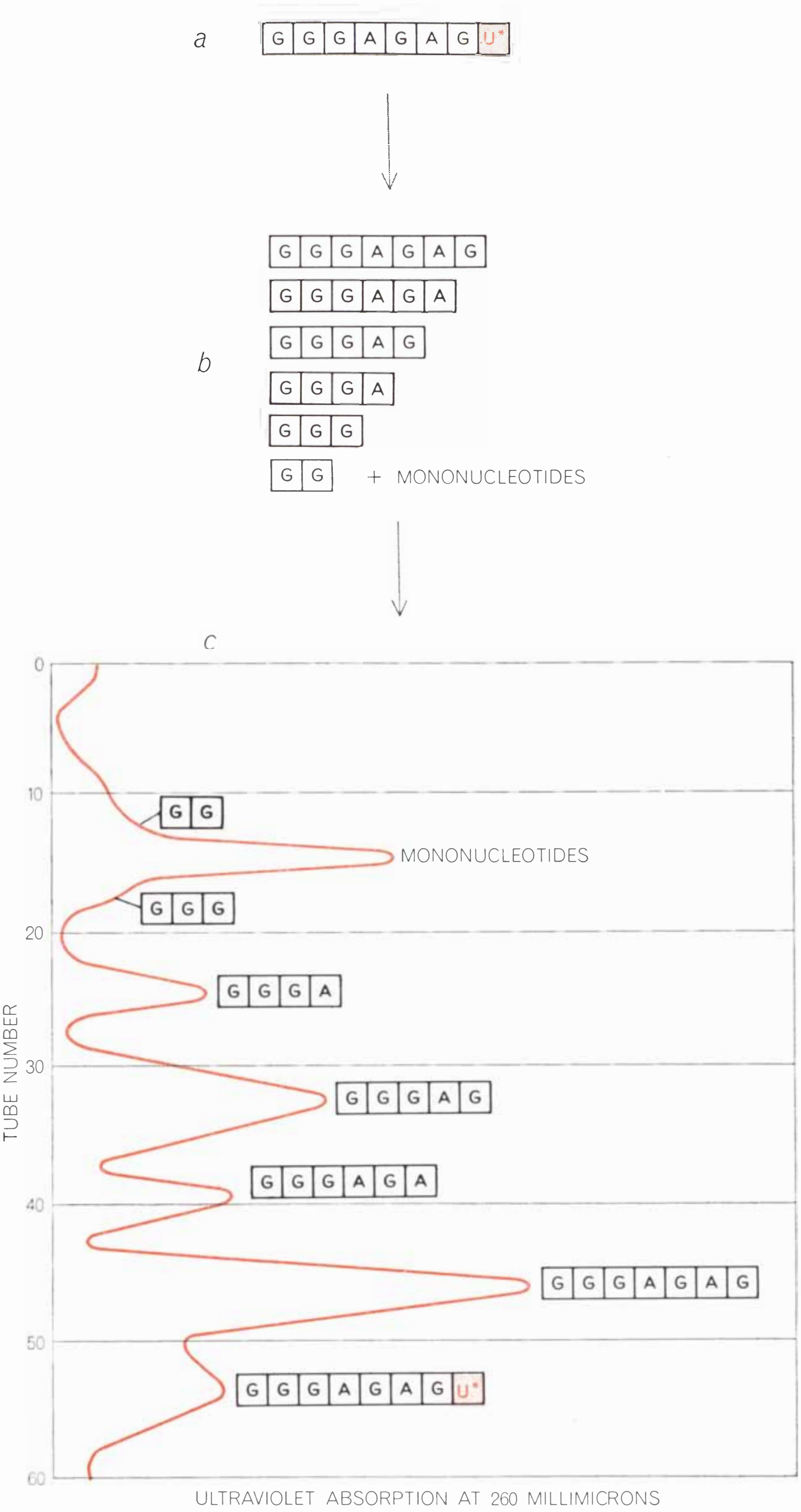
and unique short sequences made it clear that certain of the fragments found in Table 1 overlapped fragments found in Table 2. For example, there is only one inosinic acid nucleotide (I) in the molecule, and this appears in the sequence I–G–C– in Table 1 and in the sequence C–U–C–C–C–U–U–I– in Table 2. These two sequences must therefore overlap to produce the overall sequence C–U–C–C–C–U–U–I–G–C–. The information in Table 1 and Table 2 was combined in this way to draw up Table 3, which accounts for all 77 nucleotides in 16 sequences [*see illustration on page* 37].

With the knowledge that two of the 16 sequences were at the two ends, the structural problem became one of determining the positions of the intermediate 14 sequences. This was accomplished by isolating still larger fragments of the RNA.

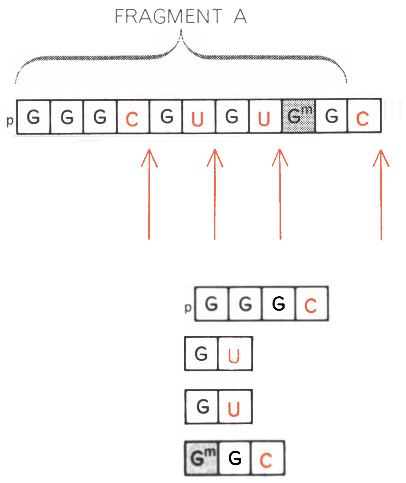
In a crucial experiment John Robert Penswick, a graduate student at Cornell, found that a very brief treatment of the RNA with ribonuclease T1 at 0 degrees centigrade in the presence of magnesium ions splits the molecule at one position. The two halves of the molecule could be separated by chromatography. Analyses of the halves established that the sequences listed in the first column of Table 3 are in the left half of the molecule and that those in the second column are in the right half.

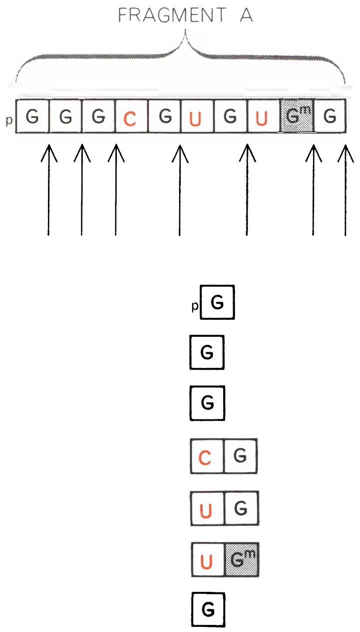
Using a somewhat more vigorous but still limited treatment of the RNA with ribonuclease T1, we then obtained and analyzed a number of additional large fragments. This work was done in collaboration with Jean Apgar and Everett. To determine the structure of a large fragment, the fragment was degraded completely with ribonuclease T1, which yielded two or more of the fragments previously identified in Table 2. These known sequences could be put together, with the help of various clues, to obtain the complete sequence of the large fragment. The process is similar to putting together a jigsaw puzzle [*see illustrations on pages 38 and* 39].

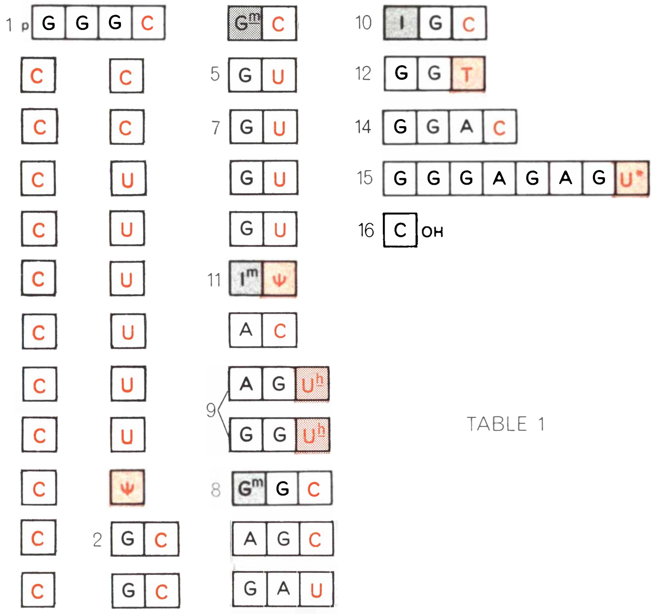
As an example of the approach that was used, the logical argument is given in detail for Fragment *A*. When Fragment *A* was completely degraded by ribonuclease T1, we obtained seven small fragments: three G–'s, C–G–, U–G–,U–G^{m}– and pG–. (G^{m} is used in the illustrations to represent 1-methylguanylic acid, another of the unusual nucleotides in alanine transfer RNA.) The presence of pG– shows that Frag-

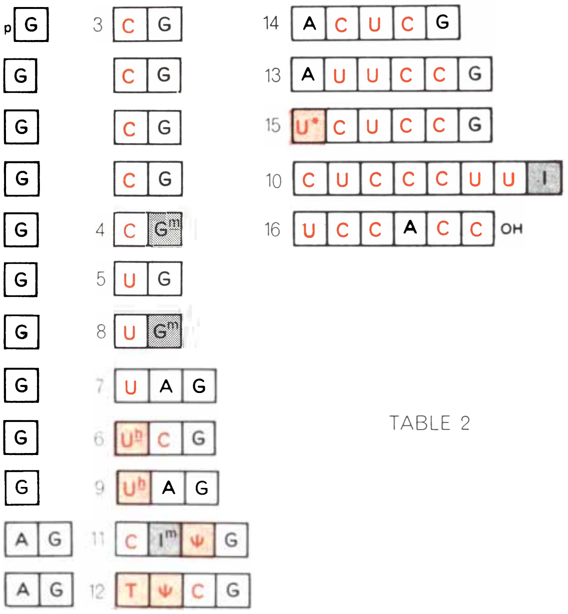


NEW DEGRADATION METHOD was developed in the author's laboratory to determine the sequence of nucleotides in fragments five to eight subunits in length. The example above begins with a fragment of eight subunits from which the terminal phosphate has been removed (*a*). When the fragment is treated with phosphodiesterase found in snake venom, the result is a mixture containing fragments from one to eight subunits in length (*b*). These are separated by chromatography (*c*). When the material from each peak is hydrolyzed, the last nucleoside (a nucleotide minus its phosphate) at the right end of the fragment is released and can be identified. Thus each nucleotide in the original fragment can be determined.









ACTION OF TWO DIFFERENT ENZYMES is reflected in these two tables. Table 1 shows the fragments produced when alanine transfer RNA is completely digested by pancreatic ribonuclease, which cleaves the molecule to the right of nucleotides containing bases with pyrimidine structures (*C, U, U^h, ψ and T*). The diagram at top left shows how pancreatic ribonuclease would cleave the first 11 nucleotides of alanine transfer RNA. The diagram at top right shows how the same region would be digested by takadiastase ribonuclease T1. Table 2 contains the fragments produced by this enzyme; they all end in nucleotides whose bases contain purine structures (*G, G^m, G^m_m and I*). The numbers indicate which ones appear in the consolidated list in Table 3 on the opposite page.

ment *A* is from the left end of the molecule. Since it is already known from Table 3 that the left terminal sequence is pG–G–G–C–, the positions of two of the three G–'s and C–G– are known; the terminal five nucleotides must be pG–G–G–C–G–.

The positions of the remaining G–, U–G– and U–G^m– are established by the following information. Table 3 shows that the U–G^m– is present in the sequence U–G^m–G–C–. Since there is only one C in Fragment *A*, and its position is already known, Fragment *A* must terminate before the C of the U–G^m–G–C– sequence. Therefore the U–G– must be to the left of the U–G^m–, and the structure of Fragment *A* can be represented as pG–G–G–C–G–...U–G–...U–G^m–, with one G– remaining to be placed. If the G– is placed to the left or the right of the U–G– in this structure, it would create a G–G–U– sequence. If such a sequence existed in the molecule, it would have appeared as a fragment when the molecule was treated with pancreatic ribonuclease; Table 1 shows that it did not do so. Therefore the remaining G– must be to the right of the G^m–, and the sequence of Fragment *A* is pG–G–G–C–G–U–G–U–G^m–G–.

Using the same procedure, the entire structure of alanine transfer RNA was worked out. The complete nucleotide sequence of alanine transfer RNA is shown at the top of the next two pages.

The work on the structure of this molecule took us seven years from start to finish. Most of the time was consumed in developing procedures for the isolation of a single species of transfer RNA from the 20 or so different transfer RNA's present in the living cell. We finally selected a fractionation technique known as countercurrent distribution, developed in the 1940's by Lyman C. Craig of the Rockefeller Institute.

This method exploits the fact that similar molecules of different structure will exhibit slightly different solubilities if they are allowed to partition, or distribute themselves, between two nonmiscible liquids. The countercurrent technique can be mechanized so that the mixture of molecules is partitioned hundreds or thousands of times, while the nonmiscible solvents flow past each other in a countercurrent pattern. The solvent system we adopted was composed of formamide, isopropyl alcohol and a phosphate buffer, a modification of a system first described by Robert C. Warner and Paya Vaimberg of New York University. To make the method applicable for fractionating transfer RNA's required four years of work in collaboration with Jean Apgar, B. P. Doctor and Susan H. Merrill of the Plant, Soil and Nutrition Laboratory. Repeated countercurrent extractions of the transfer RNA mixture gave three of the RNA's in a reasonably homogeneous state: the RNA's that transfer the amino acids alanine, tyrosine and valine [*see bottom illustration on page* 32].

The starting material for the countercurrent distributions was crude transfer RNA extracted from yeast cells using phenol as a solvent. In the course of the structural work we used about 200 grams (slightly less than half a pound) of mixed transfer RNA's isolated from 300 pounds of yeast. The total amount of purified alanine transfer RNA we had to work with over a three-year period was one gram. This represented a practical compromise between the difficulty of scaling up the fractionation procedures and scaling down the techniques for structural analysis.

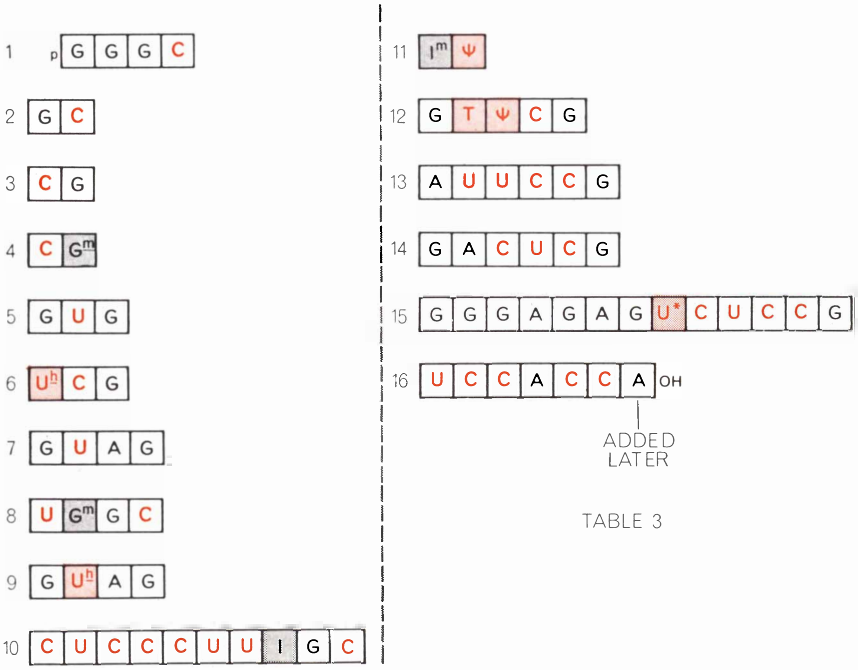
Once we knew the complete sequence, we could turn to general questions about the structure of transfer RNA's. Each transfer RNA presumably embodies a sequence of three subunits (an "anticodon") that forms a temporary bond with a complementary sequence of three subunits (the "codon") in messenger RNA. Each codon triplet identifies a specific amino acid [see "The Genetic Code: II," by Marshall W. Nirenberg; SCIENTIFIC AMERICAN, March, 1963].

An important question, therefore, is which of the triplets in alanine transfer RNA might serve as the anticodon for the alanine codon in messenger RNA. There is reason to believe the anticodon is the sequence I–G–C, which is found in the middle of the RNA molecule. The codon corresponding to I–G–C could be the triplet G–C–C or perhaps G–C–U, both of which act as code words for alanine in messenger RNA. As shown in the illustration on page 30, the I–G–C in the alanine transfer RNA is upside down when it makes contact with the corresponding codon in messenger RNA. Therefore when alanine transfer RNA is delivering its amino acid cargo and is temporarily held by hydrogen bonds to messenger RNA, the I would pair with C (or U) in the messenger, G would pair with C, and C would pair with G.

We do not know the three-dimensional structure of the RNA. Presumably there is a specific form that interacts with the messenger RNA and ribosomes. The illustration on page 31 shows three hypothetical structures for alanine transfer RNA that take account of the propensity of certain bases to pair with other bases. Thus adenine pairs with uracil and cytosine with guanine. In the three hypothetical structures the I–G–C sequence is at an exposed position and could pair with messenger RNA.

The small diagram on page 31 indicates a possible three-dimensional folding of the RNA. Studies with atomic models suggest that single-strand regions of the structure are highly flexible. Thus in the "three-leaf-clover" configuration it is possible to fold one side leaf on top of the other, or any of the leaves back over the stem of the molecule.

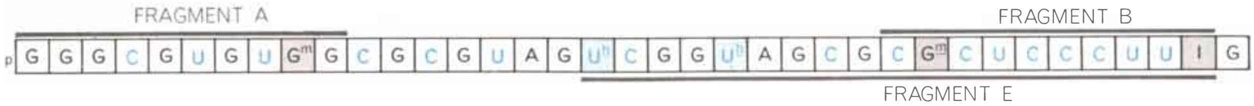
One would also like to know whether or not the unusual nucleotides are concentrated in some particular region of the molecule. A glance at the sequence shows that they are scattered throughout the structure; in the three-leaf-clo-



1	p G G G C
2	G C
3	C G
4	C G^m
5	G U G
6	U^h C G
7	G U A G
8	U G^m G C
9	G U^h A G
10	C U C C C U U I G C
11	I^m ψ
12	G T ψ C G
13	A U U C C G
14	G A C U C G
15	G G G A G A G U^* C U C C G
16	U C C A C C A OH

TABLE 3

CONSOLIDATED LIST OF SEQUENCES accounts for all 77 nucleotides in alanine transfer RNA. The consolidated list is formed by selecting the largest fragments in Table 1 and Table 2 (*opposite page*) and by piecing together fragments that obviously overlap. Thus Fragment 15 has been formed by joining two smaller fragments, keyed by the number 15, in Table 1 and Table 2 on the opposite page. Since the entire molecule contains only one U*, the two fragments must overlap at that point. The origin of the other fragments in Table 3 can be traced in similar fashion. A separate experiment in which the molecule was cut into two parts helped to establish that the 10 fragments listed in the first column are in the left half of the molecule and that the six fragments in the second column are in the right half.

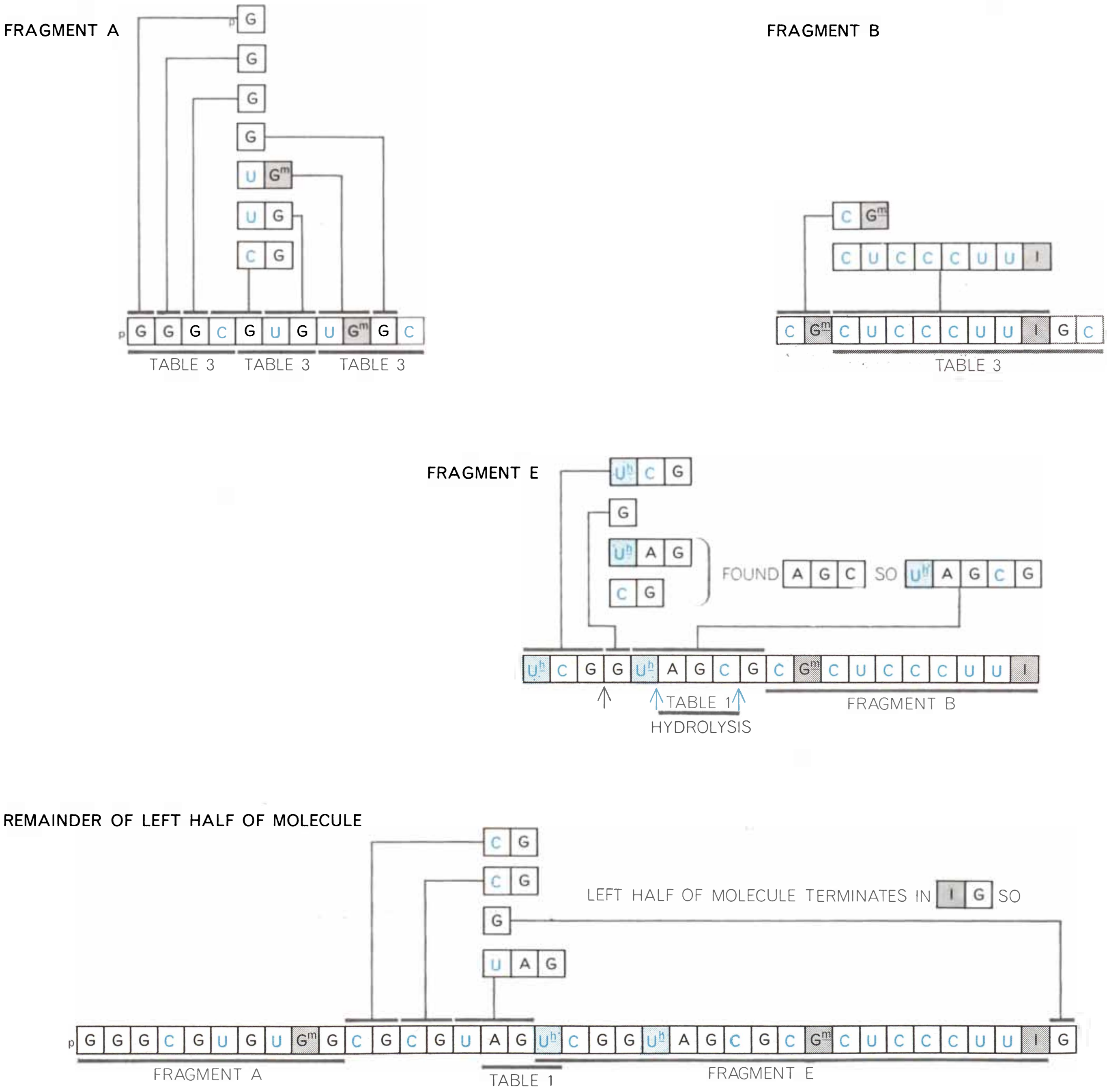


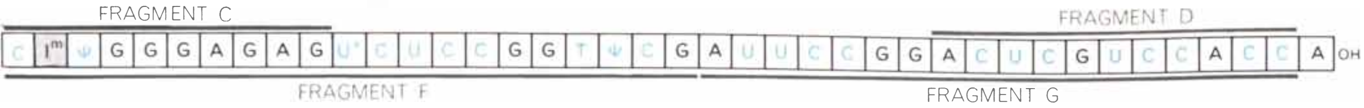
COMPLETE MOLECULE of alanine transfer RNA contains 77 nucleotides in the order shown. The final sequence required a careful piecing together of many bits of information (*see illustration at bottom of these two pages*). The task was facilitated by degrada-

ver model, however, the unusual nucleotides are seen to be concentrated around the loops and bends.

Another question concerns the presence in the transfer RNA's of binding sites, that is, sites that may interact specifically with ribosomes and with the enzymes involved in protein synthesis. We now know from the work of Zamir and Marquisee that a particular sequence containing pseudouridylic acid (Ψ), the sequence G—T—Ψ—C—G, is found not only in the alanine transfer RNA but also in the transfer RNA's for tyrosine and valine. Other studies suggest that it may be present in all the transfer RNA's. One would expect such common sites to serve a common function; binding the transfer RNA's to the ribosome might be one of them.

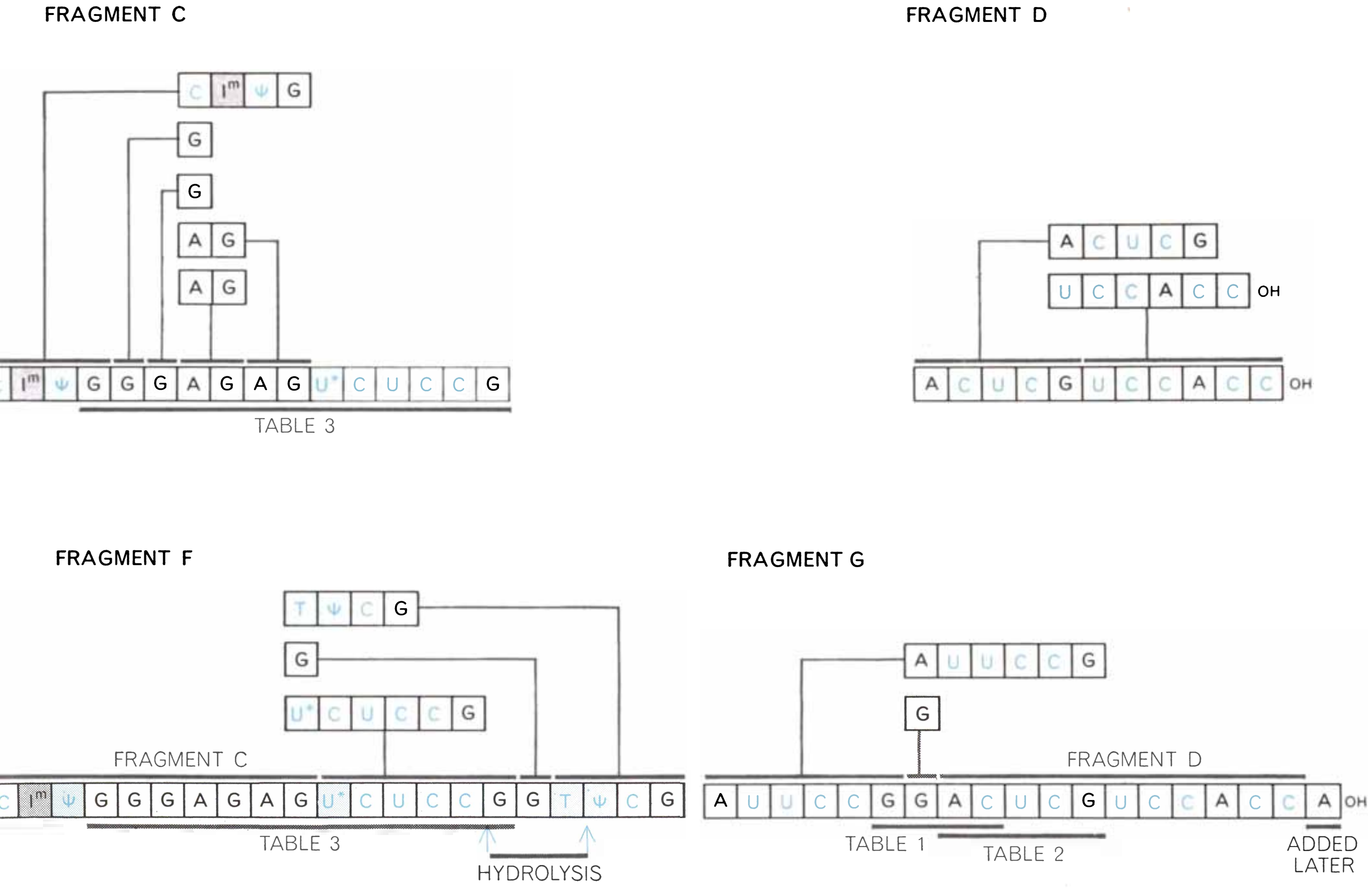
Work that is being done in many





tion experiments that cleaved this molecule into several large fragments (*A*, *B*, *C*, *D*, *E*, *F*, *G*), and by the crucial discovery that the molecule could be divided almost precisely into two halves. The division point is marked by the "gutter" between these two pages.

laboratories around the world indicates that alanine transfer RNA is only the first of many nucleic acids for which the nucleotide sequences will be known. In the near future it should be possible to identify those structural features that are common to various transfer RNA's, and this should help greatly in defining the interactions of transfer RNA's with messenger RNA, ribosomes and enzymes involved in protein synthesis. Further in the future will be the description of the nucleotide sequences of the nucleic acids—both DNA and RNA—that embody the genetic messages of the viruses that infect bacteria, plants and animals. Much further in the future lies the decoding of the genetic messages of higher organisms, including man. The work described in this article is a step toward that distant goal.



ASSEMBLY OF FRAGMENTS resembled the solving of a jigsaw puzzle. The arguments that established the sequence of nucleotides in Fragment *A* are described in the text. Fragment *B* contains two subfragments. The larger is evidently Fragment 10 in Table 3, which ends in G—C—. This means that the C—G^m— fragment must go to the left. Fragment *E* contains Fragment *B* plus four smaller fragments. It can be shown that *E* ends with I—, therefore the four small pieces are again to the left. A pancreatic digest yielded A—G—C—, thus serving to connect U^h—A—G— and C—G—. A partial digestion with ribonuclease T1 removed U^h—C—G—, showing it to be at the far left. The remaining G— must follow immediately or a pancreatic digest would have yielded a G—G—C— sequence, which it did not. Analyses of Fragments *A* and *E* accounted for everything in the left half of the molecule except for four small pieces. The left half of the molecule was shown to terminate in I—G—, thus the remaining three pieces are between *A* and *E*. Table 1 shows that one U^h is preceded by A—G—, therefore U—A—G— must be next to *E*. The two remaining C—G—'s must then fall to the left of U—A—G—. Fragment *C* contains five pieces. Table 3 (Fragment 15) shows that the two A—G—'s are next to U* and that the two G—'s are to the left of them. It is also clear that C—I^m—ψ—G— cannot follow U*, therefore it must be to the left. Fragment *D* contains two pieces; the OH group on one of them shows it to be to the right. Fragment *F* contains Fragment *C* plus three extra pieces. These must all lie to the right since hydrolysis with pancreatic ribonuclease gave G—G—T— and not G—T—, thus establishing that the single G— falls as shown. Fragment *G* gave *D* plus two pieces, which must both lie to the left (because of the terminal COH). Table 1 shows a G—G—A—C— sequence, which must overlap the A—C— in A—C—U—C—G— and the G— at the right end of the A—U—U—C—C—G—. Fragments *F* and *G* can join in only one way to form the right half of the molecule. The molecule is completed by the addition of a final AOH, which is missing as the alanine transfer RNA is separated from baker's yeast.

Neutrinos from the Atmosphere and Beyond

The first naturally produced neutrinos, by-products of high-energy cosmic-ray interactions with matter in the earth's atmosphere, have been detected in an underground laboratory in South Africa

by Frederick Reines and J. P. F. Sellschop

Two miles underground in a gold mine near Johannesburg, South Africa, an experiment is under way to study high-energy neutrinos produced by cosmic-ray collisions in the earth's atmosphere. The unusual circumstances of this investigation are characteristic of the unusual history of this most elusive of the known elementary particles. For 25 years the neutrino was little more than a figment of the theoretical physicist's imagination. Then in 1956 the first direct experimental evidence of the existence of neutrinos was obtained in the intense flux of particles emitted by a nuclear reactor. The latest chapter in the story of the neutrino is the first attempt to demonstrate the existence of neutrinos in nature. To date 10 separate events in our underground detection apparatus appear to have been produced by neutrinos originating in the atmosphere. We present here an account of the motivation and early results of this work, as well as some conjectures as to the possibility of detecting neutrinos from the sun, the other stars and the farthest reaches of intergalactic space.

It was Wolfgang Pauli who in 1930 postulated the existence of the neutrino in order to reconcile an apparent contradiction between the quantum-mechanical model of the phenomenon of nuclear beta decay and the observed products of this decay. (The term "beta decay" is used by physicists to describe the spontaneous transformation of a neutron in an unstable atomic nucleus into a proton and an electron; it is also applied to the transformation of a proton into a neutron and a positron, or positive electron.) When experimenters measured the total energy of the nuclear system both before and after beta decay, they invariably found a discrepancy in the energy budget. The observed products of the reaction not only varied in total energy from measurement to measurement; they were poorer in energy than the original nuclear system. Faced with the disturbing alternative of declaring a failure in the law of the conservation of energy, Pauli was moved to suggest a less radical solution, namely to postulate the existence of an unobserved particle that carries away the missing energy.

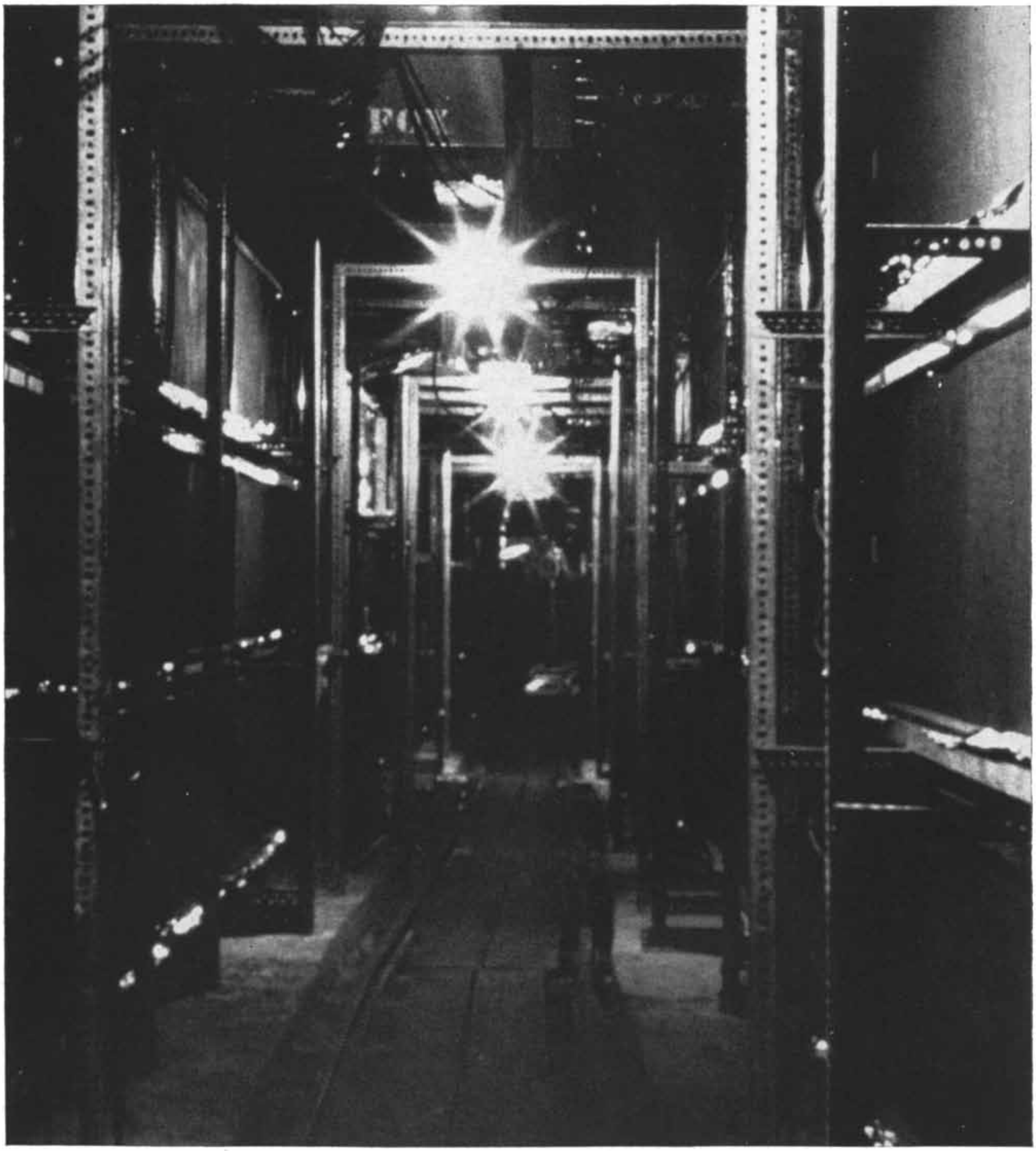
Enrico Fermi took up where Pauli left off and a few years later published a quantitative theory of beta decay, in which he introduced the concept of the "weak interaction," thus increasing the number of interactions, or forces, recognized by physicists as fundamental from two (the gravitational force and the electromagnetic force) to three. Later a fourth interaction—the nuclear, or "strong," force—was discovered, and many physicists now consider the list to be complete. The ratio of the strength of the four forces is one (gravitational) to 10^{25} (weak) to 10^{36} (electromagnetic) to 10^{38} (nuclear).

Fermi's theory was constructed in analogy to the theory of electromagnetism, which explained the production of light by atoms as the emission that occurs when an electron drops from an excited state to the "ground" state. In beta decay the de-excitation of the nucleus is accompanied by the emission not of a photon of light but of an electron and a neutrino. This de-excitation reaction leaves a nucleus whose electric charge is changed by one unit. Since the electron has exactly one unit of electric charge, it follows that the neutrino must be electrically neutral. Other observations of the beta-decay process indicate that the neutrino has an exceedingly small (if not zero) mass. It was undoubtedly with these two properties in mind that Fermi coined the name "neutrino" (Italian for "little neutral one") to denote the hypothetical particle.

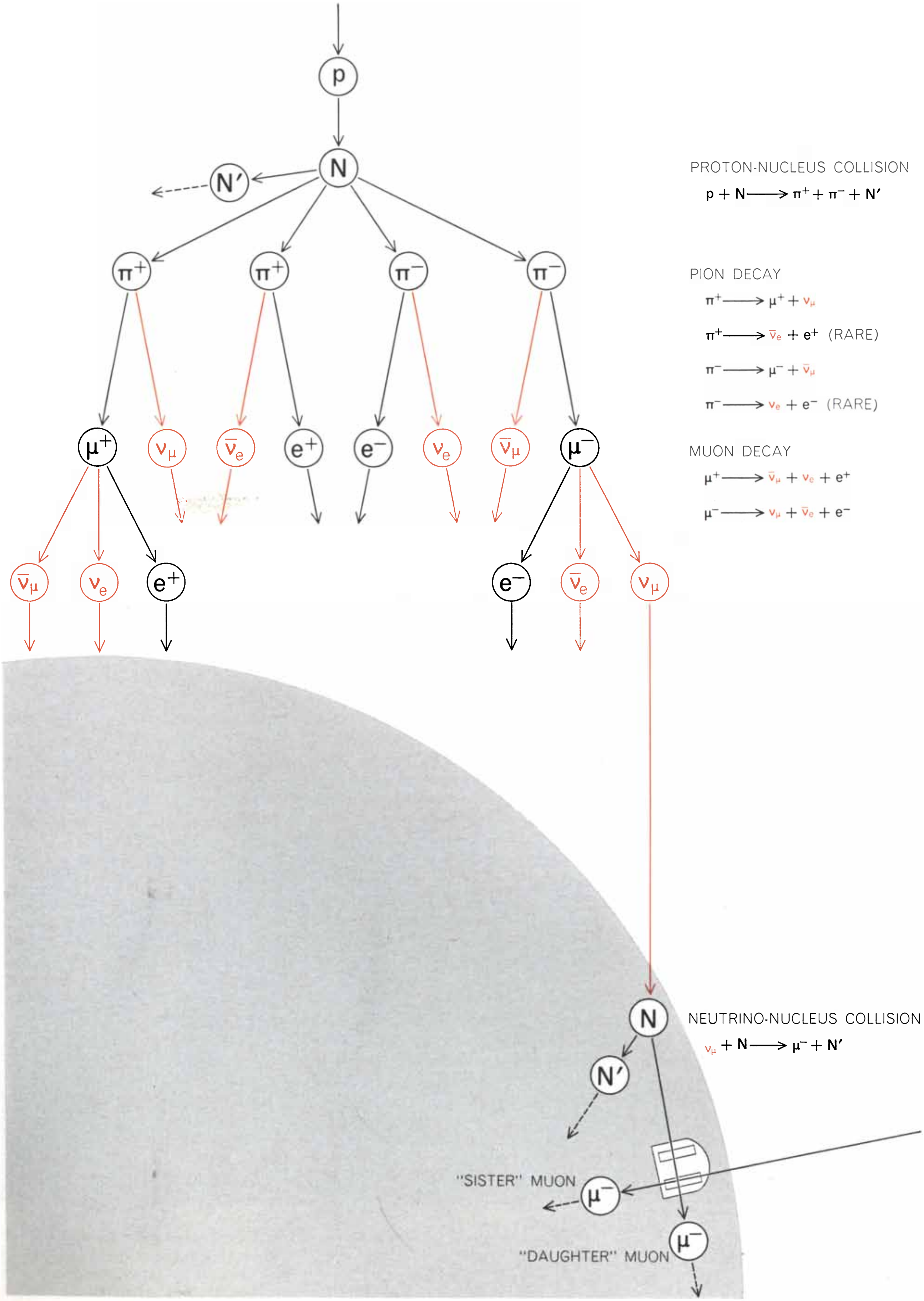
One of the most striking consequences of Fermi's weak-interaction theory is the extraordinary penetrating power it predicts for the neutrino: a neutrino with an energy of a few million electron volts, for example, could penetrate more than 100 light-years of liquid hydrogen before interacting with a hydrogen nucleus! This behavior immediately explains why the neutrino is so difficult to observe and why it is so superb a candidate for the study of the cosmos. Once produced, be it in the dense center of a star or in the extremely tenuous gas of intergalactic space, a neutrino travels unhindered (except for its minute gravitational interaction with the universe as a whole), carrying with it its initial energy, its direction and quantum characteristics—in short, a detailed record of its origin.

Because of the apparent undetectability of the neutrino away from its point of origin, it was widely believed at first to be impossible to verify the independent existence of the neutrino in a logically satisfactory manner. Hence there were legitimate grounds for skepticism among physicists as to the actuality of the neutrino until 1956, when a group of workers from the Los Alamos Scientific Laboratory led by one of the present authors (Reines) and Clyde L. Cowan, Jr., succeeded in detecting neutrinos produced by a large nuclear-fission reactor. The reaction used to detect these neutrinos was the inverse of the beta-decay reaction. The neutrinos emerging from the reactor were allowed to enter a large tank of water, where approximately one neutrino in every 10^{20} would interact with a proton in the water to produce a neutron and a positron. The observation of a positron followed closely by a neutron was taken as proof of the presence in the tank of neutrinos from the reactor.

In time it became evident that the neutrino was described by another concept in particle physics—the concept of antiparticles. Two kinds of neutrino are now associated with beta decay: those produced in the company of electrons (arbitrarily designated antineutrinos) and those produced in the company of positrons (still called neutrinos). Moreover, it was found useful to regard the particles associated with the decay of other unstable elementary particles as neutrinos. Thus the pion, or pi meson,



UNDERGROUND LABORATORY for detecting high-energy neutrinos from the atmosphere was hewn out of solid rock at a depth of 10,492 feet in a gold mine operated by the East Rand Proprietary Mines near Johannesburg. The laboratory is operated by physicists from the Case Institute of Technology and the University of the Witwatersrand. The detector elements are arrayed in racks along the sides of the 500-foot-long tunnel shown here. At the end of the tunnel is the gold-bearing "reef" that supports the mine.



PROTON-NUCLEUS COLLISION

$p + N \longrightarrow \pi^+ + \pi^- + N'$

PION DECAY

$\pi^+ \longrightarrow \mu^+ + \nu_\mu$

$\pi^+ \longrightarrow \bar{\nu}_e + e^+$ (RARE)

$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$

$\pi^- \longrightarrow \nu_e + e^-$ (RARE)

MUON DECAY

$\mu^+ \longrightarrow \bar{\nu}_\mu + \nu_e + e^+$

$\mu^- \longrightarrow \nu_\mu + \bar{\nu}_e + e^-$

NEUTRINO-NUCLEUS COLLISION

$\nu_\mu + N \longrightarrow \mu^- + N'$

spontaneously decays to form a muon, or mu meson, and a neutrino; the muon in turn decays into an electron and two more neutrinos.

A more surprising feature of the neutrino was revealed later in 1956 when experimenters working at the National Bureau of Standards, acting on the basis of a theoretical suggestion made by T. D. Lee and C. N. Yang, discovered that the neutrino does not conserve parity, that is, the mirror image of a neutrino is not a neutrino but an antineutrino. This failure of the conservation of parity was later shown to be a characteristic of all weak interactions. (In the light of the discovery it was possible to conclude that the first neutrinos detected by the Los Alamos group were actually antineutrinos.)

At this stage it was still entirely reasonable to assume that the neutral particles associated with the decay of pions, muons and other mesons were identical with those produced in nuclear beta decay. This identity was questioned by the Japanese physicist Schoichi Sakata in 1943 and by Cowan and Reines immediately after their experiment of 1956. It was not until 1962, however, that experiments to test this point were performed by a group of workers from Columbia University and the Brookhaven National Laboratory [see "The Two-Neutrino Experiment," by Leon M. Lederman; SCIENTIFIC AMERICAN, March, 1963]. Working with Brookhaven's high-energy proton accelerator, this group found that the neutrinos produced in meson decay were in fact not always identical with those produced in nuclear beta decay. Moreover, it appeared from the experiments that for certain meson decays a further distinction had to be made between the "old-fashioned" neutrinos produced in the company of electrons or positrons (called electron-type neutrinos) and a new variety produced in the company of positive or negative muons (called muon-type neutrinos). Except for the different reactions they induce, electron-type and muon-type neutrinos appear identical in all respects.

Thus in 35 years our understanding of the neutrino has advanced to the point where we now recognize it in four distinct forms. These forms, with their appropriate shorthand symbols, are the electron-type neutrino (ν_e), the electron-type antineutrino ($\bar{\nu}_e$), the muon-type neutrino (ν_μ) and the muon-type antineutrino ($\bar{\nu}_\mu$). The study of the neutrino has evolved from a hypothetical solution of a special problem into a major branch of modern physics.

The flowering of neutrino physics in recent years has in large measure been made possible by the development of machines capable of producing large numbers of both low-energy and high-energy neutrinos. The two main sources are fission reactors, which generate electron-type antineutrinos in the low-energy range (measured in millions of electron volts), and the giant charged-particle accelerators, which generate all four kinds of neutrino in the high-energy range (measured in billions of electron volts). A parallel development, just as essential to the recent achievements, has been in the area of detection techniques, specifically large scintillation counters, spark chambers and bubble chambers. With the aid of these tools physicists have continued to probe deeper into the nature of the weak interaction as revealed by neutrinos.

Lately some investigators have begun to turn their attention to the utility of the neutrino as a probe for studying the cosmos. At the same time these workers have become aware of the possibilities presented by the fact that certain neutrinos produced in nature may have a vastly greater energy than those produced by the most advanced high-energy machines. Thus neutrino astronomy has the considerable secondary attraction of providing a means for studying features of the weak interaction at energies not now attainable by artificial techniques.

The neutrinos produced in nature without the intervention of man arise from several sources. The most obvious is beta decay in the elements that compose the earth. These natural neutrinos happen to be electron-type antineutrinos with very low energies. We are more concerned here with neutrinos arising from other natural sources. These can be divided for convenience into two broad energy groups: low and high.

Low-energy neutrinos—in the range from zero electron volts to roughly 15 million electron volts—arise predominantly from the steady nuclear fires believed to power the overwhelming majority of the stars. Some neutrinos in the low-energy range, or perhaps a little higher, may be produced by nuclear reactions that occur in the explosions of supernovae.

High-energy neutrinos—ranging up to tens of thousands of billions of electron volts—originate from at least two sources. The mechanism by which neutrinos are produced in the earth's atmosphere by the collision of primary cosmic rays (mostly protons) with atmospheric atoms is fairly well known and probably predominates. There is good experimental evidence for the existence of such protons with energies as high as 10^{20} electron volts. Less is known about the second source of high-energy neutrinos, but in a way they are even more interesting. These neutrinos are produced by collisions between cosmic-ray protons and matter in the vicinity of stars and in intergalactic space. In addition, it is conceivable that neutrinos with various energies may have been produced in the reac-

p	PROTON (PRIMARY COSMIC RAY)
N	NUCLEUS
N′	RESIDUAL NUCLEUS
π^+	POSITIVE PION
π^-	NEGATIVE PION
μ^+	POSITIVE MUON
μ^-	NEGATIVE MUON
ν_μ	MUON-TYPE NEUTRINO
$\bar{\nu}_\mu$	MUON-TYPE ANTINEUTRINO
ν_e	ELECTRON-TYPE NEUTRINO
$\bar{\nu}_e$	ELECTRON-TYPE ANTINEUTRINO
e^+	POSITRON
e^-	ELECTRON

NEUTRINOS ARE PRODUCED in the earth's atmosphere by the mechanism depicted schematically on the opposite page. A primary cosmic ray, generally a proton, collides with the nucleus of an atmospheric atom (*top*), producing a shower of elementary particles, including pions. The pions then decay in flight to produce muons and muon-type neutrinos. Some of the muons in turn decay to produce additional neutrinos, of both the muon and the electron type. The experimental program pursued so far by the authors' group has been aimed at detecting the muon-type neutrinos by means of their "daughter" muons, which are produced by the interaction of these neutrinos with heavy nuclei in the earth. The daughter muons are distinguished from "sister" muons, or cosmic-ray muons born with the neutrinos in the atmosphere, by means of their angular distribution. Most of the sister muons that reach the detector area arrive from the direction of the local zenith (*bottom right*) and pass through a detector in only one of the two parallel detector rows. The daughter muons, on the other hand, arrive roughly isotropically (that is, uniformly from all directions), and of these the ones traveling in a horizontal direction locally pass through both rows of detectors. A key to the symbols used to designate the various particles is presented above.

ORIGIN	TYPE OF NEUTRINO PRODUCED	ENERGY RANGE	FLUX (NEUTRINOS PER SQUARE CENTIMETER PER SECOND)
BETA DECAY IN EARTH	$\bar{\nu}_e$	LOW	10^5 TO 10^7
COSMIC-RAY COLLISIONS IN ATMOSPHERE	ν_μ $\bar{\nu}_\mu$ ν_e $\bar{\nu}_e$	LOW TO VERY HIGH	3×10^{-3}
NUCLEAR REACTIONS IN STARS	ν_e	LOW	10^7 TO 10^{11}
COSMIC-RAY COLLISIONS IN INTERGALACTIC SPACE	ν_μ $\bar{\nu}_\mu$ ν_e $\bar{\nu}_e$	LOW TO VERY HIGH	10^{-5} TO 10^{-7}

NATURAL SOURCES OF NEUTRINOS are presented in this chart, together with the types of neutrino they produce, the energy range of their neutrinos and their contribution to the total neutrino flux at the surface of the earth. The authors' measurements have just begun to yield an experimental estimate for the flux produced by cosmic-ray collisions in the atmosphere. The figures for the two other fluxes associated with astronomical events are theoretical estimates; experiments to measure these fluxes are being planned.

tions that accompanied the beginnings of the universe, and that these neutrinos may continue to wander through space and time.

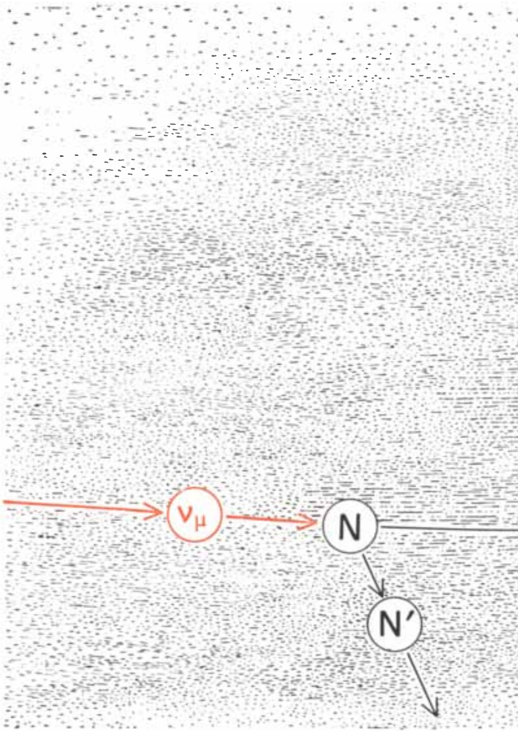
We shall consider first the high-energy neutrinos that originate in the earth's atmosphere, since this is as far as our actual experiments have progressed. When a cosmic-ray proton from outer space strikes the atmosphere, it interacts with the nucleus of an atmospheric atom in such a way as to produce a variety of elementary particles, including pions [*see illustration on page 42*]. The pions then decay in flight to produce muons and muon-type neutrinos. Some of the muons in turn decay to produce additional neutrinos of both the electron and the muon type. The total flux of the muon-type neutrinos passing through the surface of the earth from the atmosphere has been calculated to be some 30 neutrinos per square meter per second for particles with energies higher than 10 billion electron volts.

The program pursued so far by our experimental group, which is made up of workers from the Case Institute of Technology in Cleveland and the University of the Witwatersrand in South Africa, has been limited to the detection of these high-energy muon-type neutrinos. To understand why this is so it is necessary to consider for a moment the penetrating power of the various particles produced in the original cosmic-ray interaction in the atmosphere. The neutrinos, of course, have by far the greatest penetrating power, and the vast majority of them pass unimpeded directly through the earth. Consequently neutrinos produced anywhere in the earth's atmosphere can reach any point on or in the earth, provided only that they start out in the right direction.

A very small fraction (perhaps one in a million) of these neutrinos do interact with matter in the earth, and one of the products of this interaction in the case of a muon-type neutrino is a muon. Since muons are charged particles, they can in principle be observed by a number of conventional techniques.

A problem arises, however, when one seeks to distinguish between the "daughter" muons produced by neutrino interactions in the earth and the "sister" muons born with the neutrinos in the atmosphere. The difference between these two otherwise identical muons that we have sought to exploit has to do with the distribution of the angles at which they arrive. Since the primary cosmic rays are fairly isotropic (that is, they arrive uniformly from all directions), it follows that both the muon-type neutrinos and their daughter muons will also be roughly isotropic, both at the surface of the earth and in it. Now muons, because they are electrically charged, cannot penetrate matter very readily. In fact, many sister muons interact with nuclei in the atmosphere and never even reach the surface of the earth. This results in a "peaking" of sister muons toward the local zenith, because muons approaching the earth at angles away from the local zenith must pass through a larger volume of atmospheric matter.

This difference in the angular distribution of sister and daughter muons might be thought to apply also to the "sister" electrons produced with electron-type neutrinos in the atmosphere and the "daughter" electrons produced by electron-type neutrino interactions in the earth. The reason the same argument does not apply is that the mass of a muon is more than 200 times that of



NEUTRINO-DETECTION ARRAY currently in use at the authors' South African site is made up of 36 separate detector elements. Each element is called a scintillation counter and consists of an 18-foot-long Lucite box filled with scintillating liquid—mostly medicinal mineral oil—at each end an electron. As a consequence of their lightness electrons are very easily deflected and have very much less penetrating power than muons have. Electrons are effectively screened out of the detector area by even modest thicknesses of earth and so do not constitute a background problem.

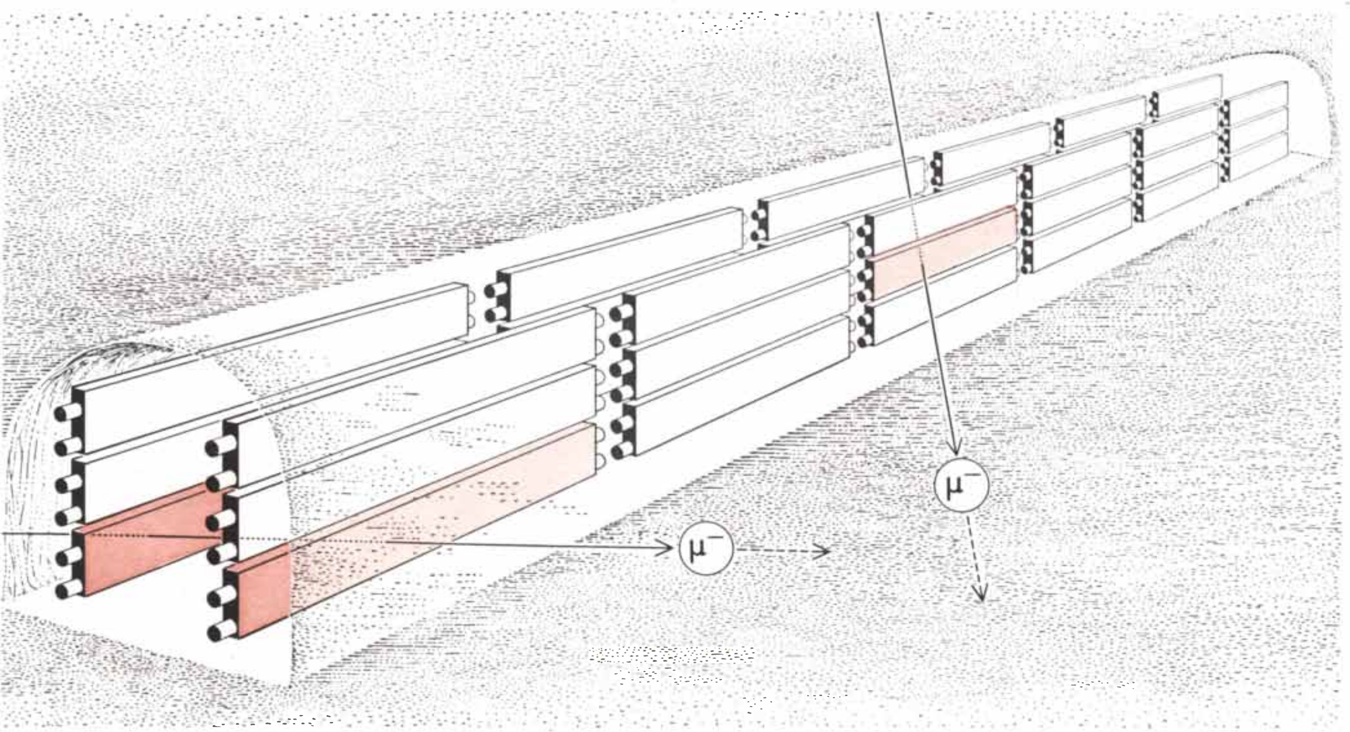
In order to design an actual experiment to detect atmospheric muon-type neutrinos by means of their daughter muons, one more fact is needed: What is the probability of a muon-type neutrino interacting with a nucleus of matter in the earth? By combining this probability with the known neutrino flux at the surface of the earth, it should be possible to predict the number of muons produced by the interaction of atmospheric muon-type neutrinos in, say, a kilogram of matter per year. Unfortunately this question of interaction probability (or "cross section," as it is called by particle physicists) has not been answered in the very high energy ranges in which we are interested, either theoretically or by experiments employing high-energy accelerators. Hence in designing our experiment we have had to make an educated guess as to the interaction probability. Indeed, one of our principal objectives is an experimental determination of the interaction probability for muon-type neutrinos, in order to understand better the nature of the weak interaction at very high energies.

From a mathematical analysis of the approach outlined above we were able to conclude that to count several high-energy atmospheric muon-type neutrinos a year would require a detection system with an effective mass of some thousands of tons. Most of the mass of the detector would consist of the target matter, which could be provided rather cheaply by allowing the neutrinos to interact with some common substance (for example rock) and then detecting the daughter muons by a large-area recording device (for example a scintillation counter).

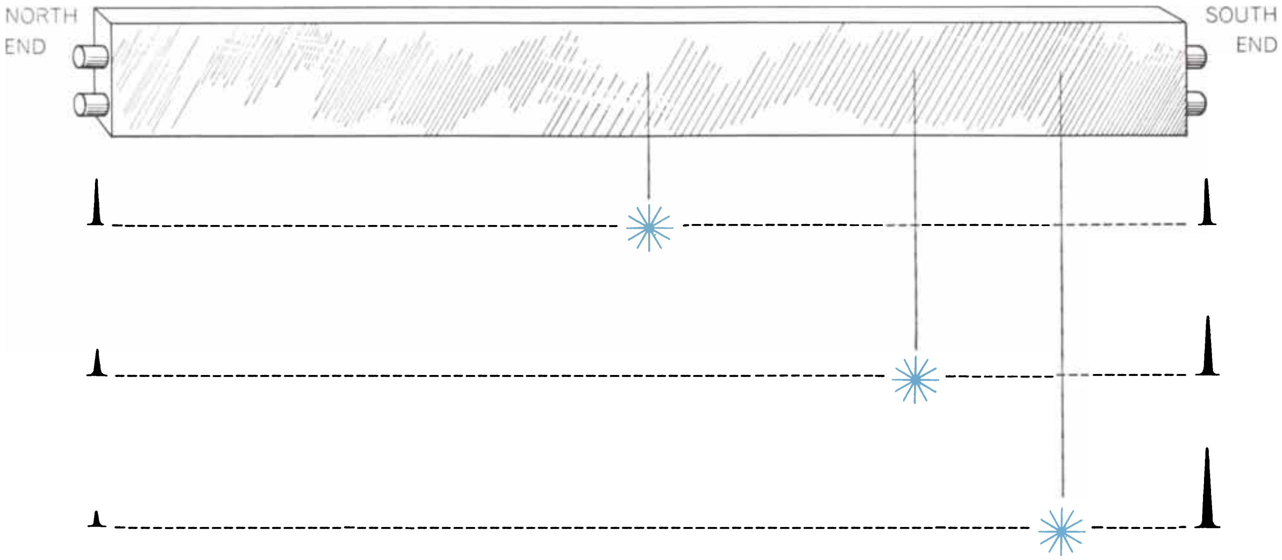
The first major difficulty encountered in pursuing such a scheme is the fact that at sea level the counts produced in the detector by sister muons from the atmosphere would be some 50 billion times more numerous than those produced by daughter muons expected from the neutrino interactions. This difficulty, combined with the approximate isotropy of the daughter muons regardless of the location of the detector, suggested that some arrangement would have to be made either to look only for neutrinos coming upward through the earth (thus discriminating against the unwanted sister muons) or to locate the detector deep in the ocean or the earth (thereby reducing the sister-muon background to manageable proportions).

In 1962 our group at the Case Institute decided that an underground arrangement would be the simplest, provided that a deep enough site of adequate extent could be found, and that a detector could be made to discriminate between particles traveling in a predominantly vertical direction (the sister muons produced by cosmic-ray collisions in the atmosphere) and those traveling in all other directions (the daughter muons produced by neutrino interactions in the rock).

All that remained was to find a suitable site and then to build, install and operate the equipment. A worldwide search resulted in the selection of an excellent location in the East Rand Proprietary Mines near Johannesburg. There space for a laboratory was specially hewn out of solid rock 10,492 feet below the surface. The laboratory con-



of which are two photomultiplier tubes. When a charged particle (in this case a muon) traverses the liquid, it loses energy, some of which appears as a flash of light (*color*). The photomultiplier tubes convert the light into an electrical pulse, which is then analyzed. In order to distinguish between muons traveling horizontally and those traveling vertically, the detectors are arranged in two parallel horizontal rows, with the broad faces of the boxes sideways. The detectors are stacked three high in order to measure three different angular ranges. Two muons are shown being detected. Entering from the left and passing through a detector in each row is a daughter muon produced by the interaction of an atmospheric muon-type neutrino with the surrounding rock. Entering from the top and passing through just one detector is a sister muon produced by a cosmic-ray interaction in the atmosphere.



ELECTRICAL PULSES from the four photomultiplier tubes on each detector element can be analyzed to give the position along the tank at which the muon penetrated, as well as the energy deposited in the tank by the muon. Pulses at each end of the tank are given for three muon-produced scintillations (*colored stars*). It is this capability that makes the detector array a crude telescope.

sists of a large entry area, which contains the bulky electronic equipment, and a tunnel 500 feet long and eight feet in diameter, where the detector elements are installed [*see illustration on page 41*]. At the end of the tunnel is the gold-bearing "reef" that supports the mine. The work of the laboratory, in which the original Case group has been joined by investigators from the nearby University of the Witwatersrand, is supported by the U.S. Atomic Energy Commission.

Since no one had ever observed cosmic rays at such depths, it was necessary to extrapolate the cosmic-ray intensities observed at lesser depths in order to estimate the background muon flux caused by sister, or cosmic-ray, muons at the level of our laboratory. A conservative extrapolation indicated that of the roughly 150 sister muons per year that would penetrate a detector 110 square meters in area, scarcely one could be expected to be traveling at an angle of more than 45 degrees to the vertical. Thus we concluded that our experiment for detecting muon-type neutrinos from the atmosphere would be feasible at a depth of two miles if the detection system had a simple angular sensitivity.

In its final form the detector array, which is built up of 36 separate scintillation counters, is actually a crude telescope, since the path of a muon can be inferred from the signals it produces in the detector elements. Each detector element consists of an 18-foot-long Lucite box filled with scintillating liquid—mostly medicinal mineral oil—at each end of which are two photomultiplier tubes. When a charged particle (in this case a muon) traverses the liquid, it loses energy, some of which appears as a faint flash of light. The light is trapped in the box by the optical process known as total internal reflection and is transmitted to the ends, where the photomultiplier tubes are situated. In the photomultiplier tubes the light pulse is converted to an electrical pulse, which is amplified and sent by coaxial cable to the electronics area for analysis. The pulses from the four photomultiplier tubes on each detector element can be analyzed to give the position along the tank at which the particle penetrated, as well as the energy deposited in the scintillating liquid by the particle [*see illustration above*].

The arrangement of the detector elements with respect to the target rock was designed to distinguish between muons traveling horizontally and those traveling vertically. This was accomplished by placing the detectors in two parallel horizontal rows, with the broad faces of boxes sideways [*see illustration on preceding page*]. The detectors were stacked three high in order to measure three different angular ranges. By virtue of its size and its geometry this arrangement is the most sensitive neutrino detector yet assembled.

Although such an undertaking is simple enough in concept, there are complexities associated with the sheer scale of it. The detector equipment includes five miles of cable, 4,400 gallons (16 tons) of scintillating liquid, 144 photomultiplier tubes and a structural framework 120 feet long. The logistics of manning the operation are illustrated by the fact that members of our group have logged a total of 500,000 miles of travel between the U.S. and South Africa in the past two years.

On October 27, 1964—13 months after the selection of the South African site—our equipment registered the first deep-underground observation of a sister, or cosmic-ray, muon. Then on February 23, 1965, the detectors recorded a muon that had traveled in a horizontal direction—the first "natural" high-energy neutrino had been observed! Since last February we have observed in our equipment some 80 sister muons and 10 daughter muons. These statistics are beginning to yield the first experimental estimate of the interaction probability for high-energy neutrinos.

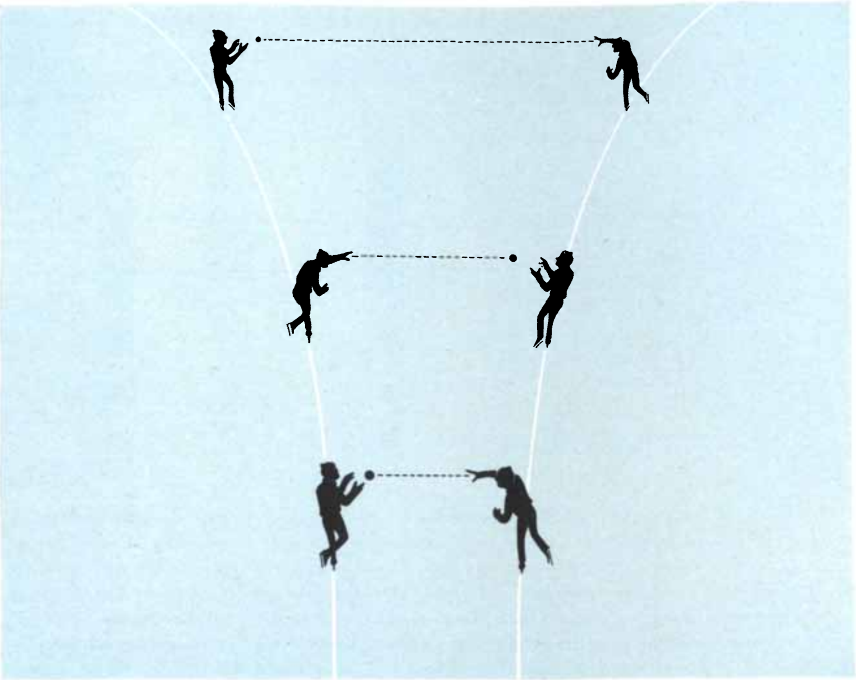
We have been on the alert for one kind of neutrino-produced event in particular because of its possibly great theoretical significance. Such an event would be recorded simultaneously in two tanks on each side of the detector array. An interpretation of this kind of event is worth discussing here in some detail.

One of the most serious questions facing theorists studying the weak interaction today has to do with a hypothetical particle called the intermediate vector boson, which has been postulated in order to explain the weak interaction in a manner analogous to that in which theorists explain the other fundamental forces. For example, it is a feature of all theoretical models of the strong nuclear force that this force results from an exchange between the interacting particles of a third particle—a meson. This situation can be visualized by imagining two boys playing catch on ice skates [*see top illustration at right*]. Each time the ball is thrown the thrower recoils, and each time the catcher catches he recoils. The exchange of the ball produces an apparent repulsive force between the two boys. If, as Denys Wilkinson of the University of Oxford suggests, the exchange were not of a ball but of a boomerang, then the force would appear attractive: the thrower would aim away from the receiver, and the receiver would catch the boomerang facing away from the thrower [*see bottom illustration at right*].

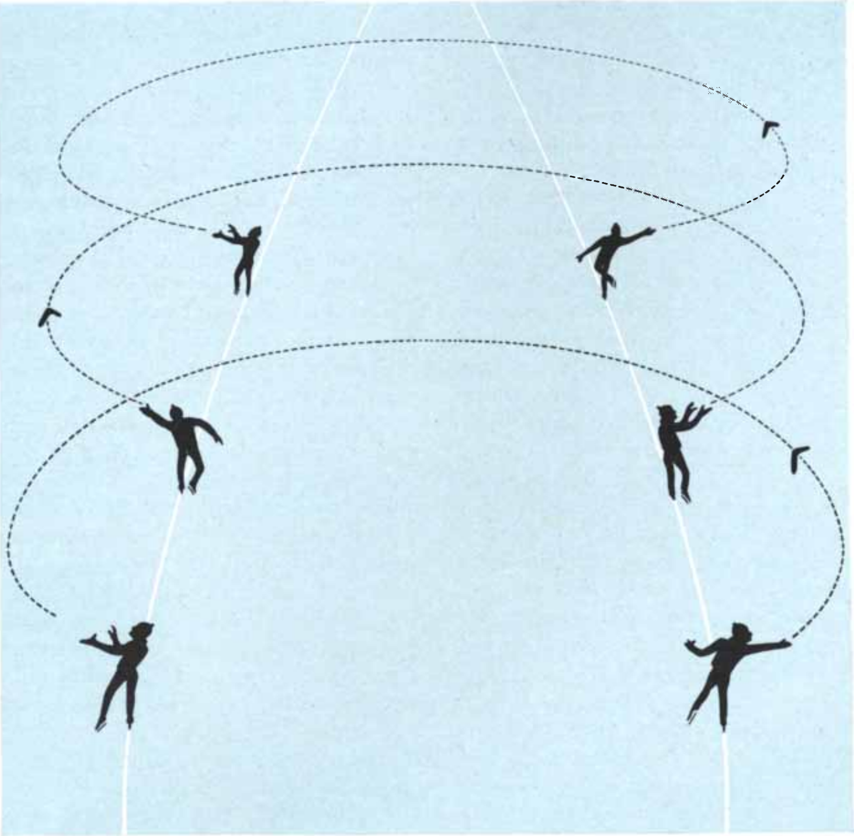
The relevance of the analogy is that the attraction of two particles in an atomic nucleus can be explained by the exchange of a particle that is attractive to each. The exchanged particle, a meson, is said to mediate the interaction. The same idea of a "nonlocal" force has been applied by theorists to the weak interaction, and the hypothetical mediating particle is the boson. So far experimenters have sought in vain for the boson with high-energy particle accelerators. As a result of their search a lower limit has been set for the mass of the boson; if it exists, it must be too heavy (more than twice the mass of the proton) to be produced at the energies currently available in the laboratory.

The question at issue is: Are the cosmic-ray neutrinos energetic enough to produce bosons? If bosons exist and if they are produced by neutrino interactions in rock, their signature would be two nearly parallel muon tracks starting from a common origin and penetrating the detector elements at two places on each side of the detector array [*see illustration on next page*]. If it could be demonstrated that the two muons originated deep enough in the rock, this would be the most likely interpretation of such an observation. Unfortunately, although we have observed an event that can be interpreted in this way, it was not possible to locate the common point of origin with any precision, and the interpretation remains ambiguous.

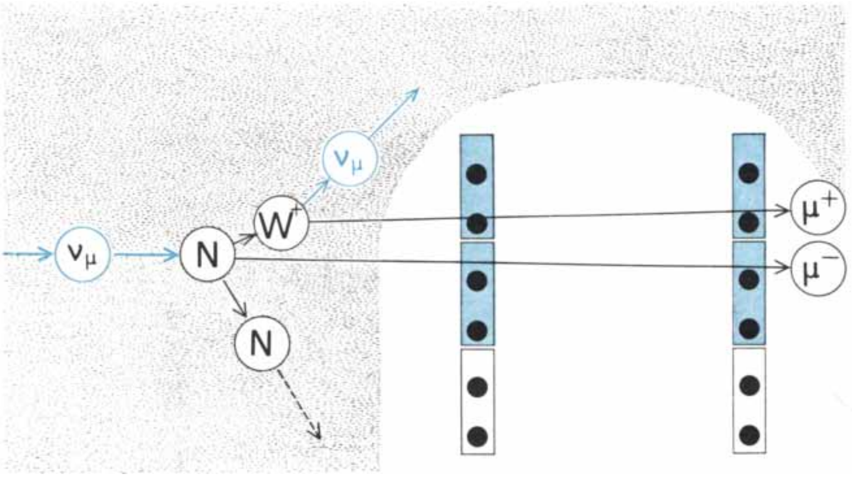
To date the only other experimental evidence that may relate to this important question is an event reported by a group of Indian, Japanese and British investigators working in a mine in the Kolar goldfields west of Bangalore in India. Operating at a depth of 7,600 feet with a detector somewhat smaller than ours, these workers have recorded a definite two-track event. As



SKATER ANALOGY is an aid to visualizing the theoretical model in which a force is represented as an exchange between the interacting particles of a third, or mediating, particle. The exchange of a ball produces an apparent repulsive effect between the two skaters. Each time the ball is thrown the thrower recoils, and each time the catcher catches he recoils.



ATTRACTIVE FORCE can be represented using the skater analogy by substituting a boomerang for the ball. The thrower aims away from the receiver, and the receiver catches facing away from the thrower, producing an apparent attractive force. The boomerang variation of the skater analogy was suggested by Denys Wilkinson of the University of Oxford.



EVIDENCE for the existence of the intermediate vector boson, the hypothetical mediating particle of the weak interaction, would be provided by the observation of two nearly parallel muon tracks, starting from a common origin (an atmospheric-neutrino interaction with surrounding rock) and penetrating two detector elements in each row. Two events that can be interpreted as resulting from such a muon pair have been detected, one by the authors' group and another by an experimental group in India, but it is entirely possible to interpret these findings without involving the boson. Boson is designated W^+ in this decay mode.

they point out, however, their result can be interpreted without involving the boson. The two tracks may be produced by a neutrino-produced pion-muon pair, the same phenomenon that frustrated those who sought the boson with high-energy accelerators.

In order to find an answer to this question our equipment has been improved in various ways and is in the process of being enlarged to a total length of 220 feet to increase its sensitivity. In addition, work has begun on the construction of a new, slightly deeper laboratory at the same site, in which we plan to operate an elaborate spark-chamber system for obtaining more precise directional information regarding sister- and daughter-muon fluxes. The sensitivity of the new spark-chamber system will be at least four times that of the original scintillator array.

At this stage in our experiments we have no evidence for natural neutrinos other than those from the atmosphere, although what we have observed may include a small admixture of neutrinos from outer space. As the detection systems increase in size and angular resolution, we should be able to search more sensitively for these elusive messengers. Jack W. Keuffel of the University of Utah is engaged in building a large muon detector that has interesting possibilities in this regard. Some of us at Case are thinking of a 100,000-ton spark-chamber array deep underground. Mining technology can now provide laboratory space for such an array at a depth of 15,000 feet. Better still would be a detector on the moon to escape the background of atmospheric neutrinos. Such a colossal lunar-based detector would necessarily be made largely of materials found on the moon. Fortunately there are several more immediate possibilities.

It turns out that if we were to lower our sights, so to speak, from the high-energy range to the range of from six million to 15 million electron volts, our present South African laboratory would be particularly well suited, by virtue of its extremely low background of cosmic-ray particles, for "seeing" the sun by means of the neutrinos it emits. According to current theoretical models of the sun, one of the by-products of the nuclear reactions that power the sun is an unstable isotope of boron (boron 8) that undergoes beta decay to yield electron-type neutrinos with energies up to 14 million electron volts. It has been calculated that the intensity of such neutrinos striking the earth is on the order of 10 million per square centimeter per second. Although the beta decay of boron 8 is responsible for only a small fraction of the total energy produced by the sun, it is particularly attractive to prospective neutrino astronomers because of all the sources of solar neutrinos only this one is energetic enough to stand out above the natural background flux.

At a mine in South Dakota, Raymond J. Davis, Jr., of Brookhaven is engaged in building a giant radiochemical detector that should be able to detect the predicted flux of electron-type neutrinos from the sun. This experiment, like ours, employs an inverse beta-decay process, although at lower energies; in it the neutrino interacts with the nucleus of a chlorine atom to produce an unstable atom of argon 37. The chlorine nuclei are contained in a 100,000-gallon tank of tetrachloroethylene (C_2Cl_4), an ordinary cleaning fluid. The electrons from the decaying argon-37 atoms are detected by an array of Geiger counters. A count rate of about five per day would be important evidence for the influence of electron-type neutrinos from the sun. Other detectors working on the inverse-beta-decay principle, but counting each event as it occurs rather than using the radiochemical approach, are under construction in the U.S. by members of the Case group.

Another approach that may provide direct evidence of the presence of boron 8 in the sun employs the process of elastic scattering of electrons by solar neutrinos. The phenomenon of elastic scattering of neutrinos by electrons was predicted by Richard P. Feynman and Murray Gell-Mann of the California Institute of Technology and by Robert E. Marshak and E. C. G. Sudarshan of the University of Rochester. Although it is generally believed to exist, such scattering has not yet been observed in the laboratory. In this process the electron-type solar neutrinos give the target electrons a "kick," which can be measured by a detector. The energy of the neutrinos can then be deduced from the magnitude of the kick. Since the target electrons can only be kicked a few inches at most, they must be located within the detector itself. The expected number of such kicks due to low-energy solar neutrinos has been estimated at some 10 per year for every 1,000 gallons of scintillating liquid. It now appears feasible to construct suitable detectors in this energy range, and a pilot model is already under construction at our South African site.

We are now on the verge of studying neutrinos from the sun, and in the next year or two these observations should decide whether the current model of the sun is correct or requires modification. It is difficult to predict the future of neutrino astronomy, but it seems likely that what began 35 years ago as an ingenious apology for an untraceable loss of energy will eventually enable physicists not only to probe the fundamental forces of nature on the subatomic scale but also to reveal much about processes at the center of the sun and perhaps more distant celestial events as well.

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In putting lecture slides together, regular projection facilities are no longer required. The new self-contained KODAK READYMATIC Viewer works quite cozily in close quarters, is silent, weighs only 7 pounds, sets up instantly, can be obtained for less than $50 from the nearest convenient camera shop. Have the department get one.

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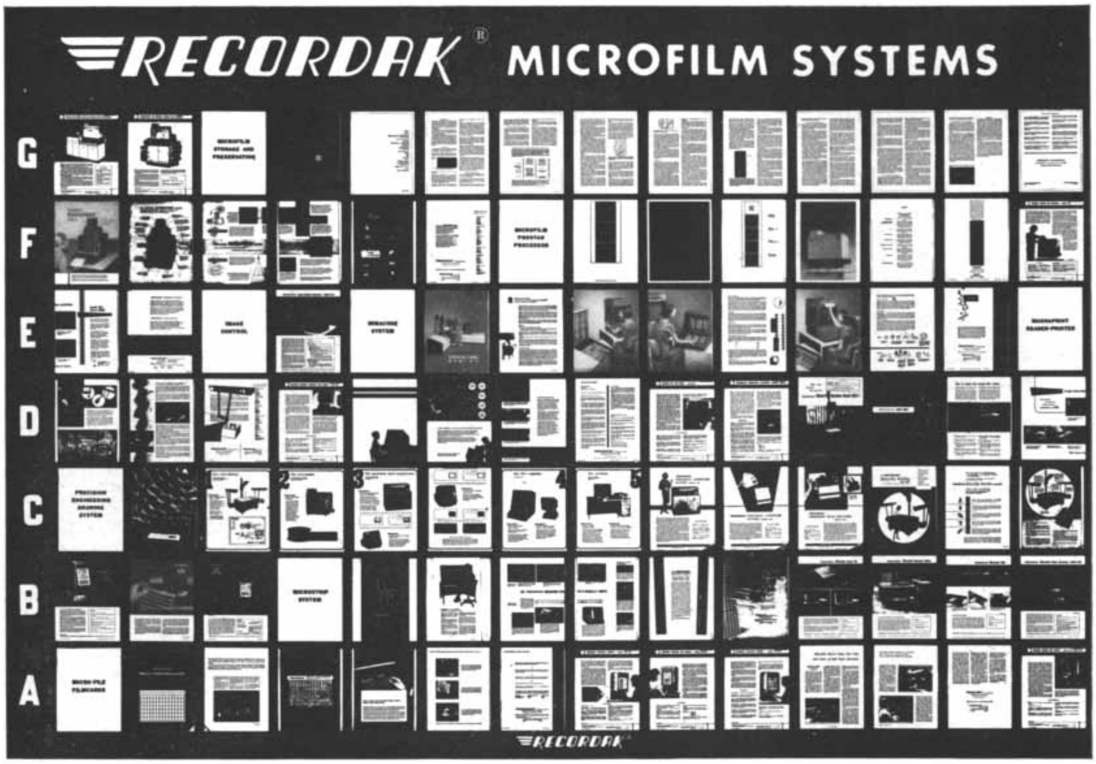

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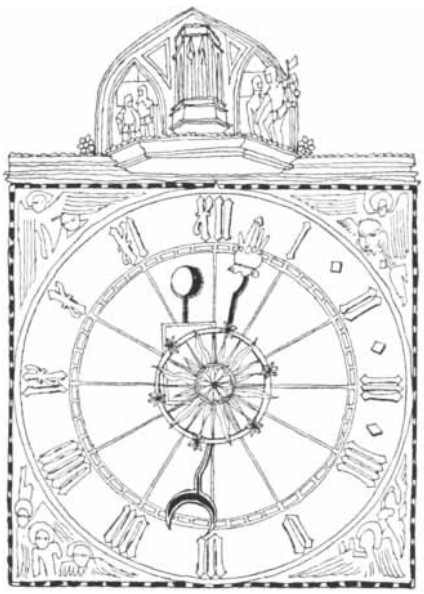


Coal Power v. Nuclear

Twenty-four years after the first controlled release of nuclear energy, U.S. utilities are operating a dozen nuclear power plants with a total installed generating capacity of about 1,000 megawatts. This is about half of one percent of the nation's total electric generating capacity. It is estimated that over the next decade nuclear power will be capturing between 10 and 15 percent of the new steam-electric-plant market and that by the early 1980's about 35 percent of all new steam-electric plants will be nuclear. These estimates are provided by Arthur D. Little, Inc., the Cambridge, Mass., industrial consulting firm.

The nation's first "full scale" nuclear plant went into operation in 1957 at Shippingport, Pa. Not intended to be economically competitive, it generates 60 megawatts of electric power. Today several nuclear plants with a capacity of about 200 megawatts each are producing electric power at a cost of about one cent per kilowatt-hour, a figure only slightly higher than that for conventional power in the same areas.

The most optimistic cost projection based on available technology was recently made for the Jersey Central Power and Light Company. It is estimated that its proposed Oyster Creek plant, with a designed capacity of 515 megawatts, will produce power at about half a cent per kilowatt-hour, and that when capacity is stretched to 620 megawatts, the power cost will drop to almost .4 cent.

The fuel with which nuclear fuel competes in most of the U.S. is coal. At its designed capacity the Oyster Creek plant will produce power slightly more cheaply than a coal-fired plant burning coal priced at 26 cents per million British thermal units, or just about the average price paid by all U.S. utilities. When the Oyster Creek plant is stretched to 620 megawatts, coal would have to be available at 20 cents per million b.t.u. to be competitive. The latter figure would make nuclear power competitive with coal in many sections of the country. The analysts for Arthur D. Little believe that the average price of coal will probably drop by as much as 25 percent in the next decade, chiefly as a result of lower transportation costs, but that the drop will be more than offset by continued improvements in nuclear-power technology.

Quasars (Cont.)

Quasars—quasi-stellar radio sources—continue to hold the center of the stage in astronomy. At a recent meeting on the observational aspects of cosmology, sponsored by the University of Miami, astronomers were told (1) of a quasar whose apparent speed of recession exceeds that of any other known object, (2) of new measurements showing that the radio output of some quasars is changing rapidly, (3) of the first observational evidence that at least one quasar is a remote object and not merely a nearby one receding at high velocity and (4) of a direct measurement, aided by a quasar, of the amount of neutral (un-ionized) hydrogen in intergalactic space.

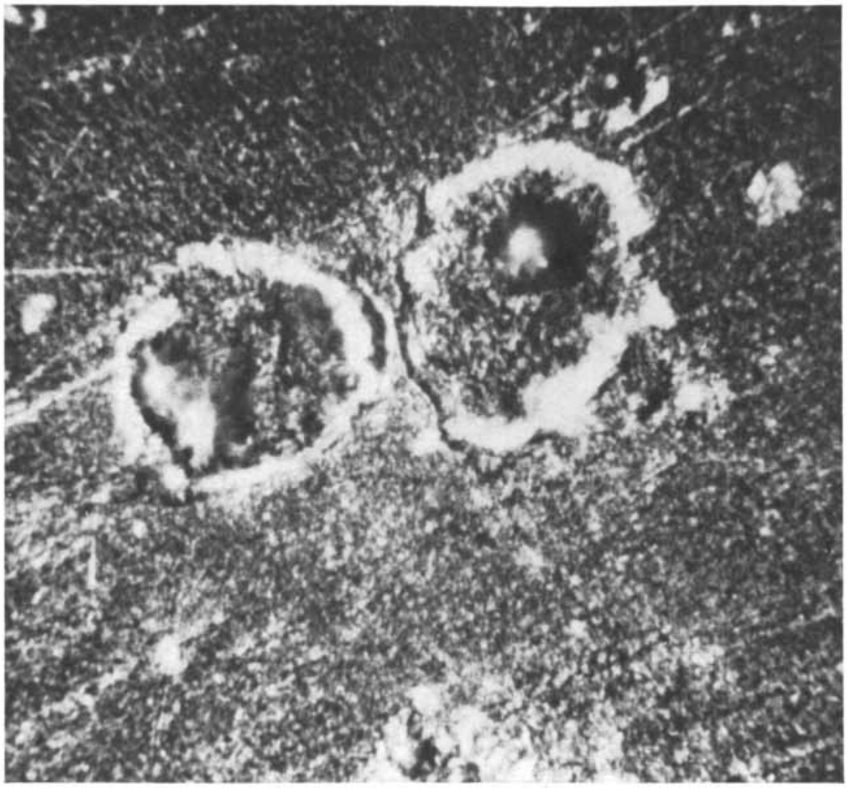
The fastest-receding object was reported by Margaret E. Burbidge of the University of California at San Diego. Using the 120-inch reflecting telescope at the Lick Observatory, she found a quasar that is receding at 81 percent of the velocity of light, slightly exceeding the 80 percent velocity of recession previously reported for the quasar 3C 9. The remoteness of such objects can only be guessed at, but it is believed to be on the order of five billion to 10 billion light-years.

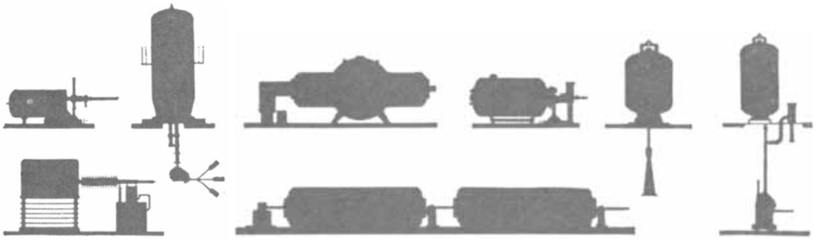
W. A. Dent of the Radio Astronomy Observatory of the University of Michigan reported that at the radio wavelength of 3.75 centimeters the output of the quasar 3*C* 273 had increased 42 percent over the past three years. In the same period the output of the quasars 3*C* 279 and 3*C* 345 had decreased 48 percent and 36 percent respectively. Dent also reported a 40 percent increase over three years in the radio output of NGC 1275, which is not a quasar but a type of radio-emitting galaxy. This was the first finding of a pronounced variation in the output of a radio source other than a quasar.

Prior to Dent's observations it was known that quasars have a variable light output, but it was thought that the radio output originated in a much larger volume and would therefore be more constant. Alan T. Moffet of the California Institute of Technology reported that the variations in the radio output of 3*C* 273 cut off sharply at wavelengths between 21 and 31 centimeters. He deduced from this that the quasar may have a diameter of no more than about 13 light-years. If 3*C* 273 is as remote as it is assumed to be, its angular diameter, as viewed from the earth, must be only about .001 second of arc, which would be a factor of 100 below the resolving power of observational techniques now available to radio astronomers.

Evidence that 3*C* 273 is truly remote and not merely a nearby object that is receding at high velocity was presented by J. A. Koehler of the Arecibo Observatory in Puerto Rico. Using the 210-foot radio telescope at Parkes in Australia, he found that some of the 21-centimeter radiation from 3*C* 273 had apparently been absorbed by a cloud of neutral hydrogen that may be associated with the Virgo cluster of galaxies, which is estimated to be about 40 million light-years away.

J. E. Gunn of the California Institute of Technology reported that he and Bruce A. Peterson had been able to estimate the total amount of neutral hydrogen in intergalactic space by observing radiation that had originated in the ultraviolet part of the spectrum in the quasar 3*C* 9, but had been shifted by the Doppler effect so that it reached the earth in the visible part of the spectrum. The radiation concerned was the Lyman-alpha radiation emitted by hydrogen atoms at a wavelength of 1,216 angstroms. A portion of this ra-





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GT&E SUBSIDIARIES: Telephone Operating Cos. • GT&E Laboratories • GT&E International • General Telephone Directory • Automatic Electric • Lenkurt Electric • Sylvania Electric Products diation would be absorbed by neutral hydrogen atoms in intergalactic space. Gunn computed that at the time the Lyman-alpha radiation left 3C 9, several billion years ago, the amount of neutral hydrogen in space was about one atom in 10^{10} cubic centimeters, or about 100,000 atoms in one cubic kilometer. If this value is correct, it indicates that most of the matter in the universe was then in some form other than neutral hydrogen—perhaps in the form of ionized hydrogen.

Transferable Drug Resistance

Recent experiments have provided new information on an extraordinary but little-known phenomenon: transferable drug resistance. The fact that some forms of resistance to antibiotics by microorganisms are "contagious" was discovered by Japanese workers in 1959. They found that resistance in a given species is not necessarily the result of a chance mutation in that species, followed by natural selection of the resistant strain. Instead, the genetic determinants for resistance—and usually for multiple resistance to several antibiotics—can be transferred from the cells of one strain of bacteria to cells of another strain or of another species, genus or even family, and can therefore appear suddenly and on a large scale in previously drug-susceptible organisms.

The Japanese investigators showed that in the intestinal bacterium *Shigella dysenteriae* the acquisition of resistance depends on the transfer of an extrachromosomal genetic element, located in the cytoplasm of the cell, during the cell-to-cell mating process known as conjugation. Apparently this element has two functional parts: the resistance determinant itself and a transfer factor that gets it from one cell to another. The two are linked genetically, and the intact unit is required for the transfer of resistance.

Now E. S. Anderson and M. J. Lewis of the Central Public Health Laboratory in London have reported in *Nature* and the *British Medical Journal* that in the intestinal bacterium *Salmonella typhimurium* either extrachromosomal transfer factors or extrachromosomal but nontransferable resistance determinants can often exist alone in different naturally occurring strains. When the two kinds of element meet in a cell, a transferable resistance factor is formed. Anderson and Lewis mix three cultures: a drug-sensitive *S. typhimurium* that carries a transfer factor, a resistant *S. typhimurium* that carries no transfer factor and an *Escherichia coli* that carries neither a transfer factor nor a resistance determinant. The result is that the transfer factors migrate into the cells of the resistant strain and combine with their resistance determinants; the complexes are transferred to the *E. coli* cells, which acquire transferable resistance. By varying the experiment, the transfer factors can be made to migrate from sensitive donor cells to a resistant strain where they mobilize resistance determinants, and then to return to confer transferable resistance on the previously susceptible donor cells.

Resistance transfer has been shown to take place in the intestines of animals and human beings. There the frequent presence, particularly in farm animals, of an antibiotic would favor the selective multiplication of organisms bearing the proper resistance factor. Anderson and Lewis have noted a sharp increase in the prevalence of multiple antibiotic resistance in cultures of a certain type of *S. typhimurium* that infects cattle as well as human beings, and they suggest that this may be due to the free use of antibacterial drugs in livestock rearing.

Compromise

In the years since World War II the administrators of U.S. universities have been chronically troubled by the problem of how to provide facilities for classified research while avoiding what McGeorge Bundy has called "the hampering and restrictive influence of secret work." Some institutions have adopted a policy of banning secret research except in time of all-out war. (Bundy's statement was made in defense of Harvard University's policy, which falls in this category.) Other universities have actively sought contracts for such research; still others have adopted a middle position.

The University of Pennsylvania has been pressed to define its policy by a group of students and faculty members who allege that university laboratories are being used for research in biological warfare and for other classified projects. The group states that secret work is incompatible with an atmosphere of free inquiry and that work "designed to turn knowledge willfully to destructive ends violates the moral principles and compromises the intellectual integrity of the university." The Faculty Senate has voted against a resolution condemning paramilitary research, but it has upheld the other aspect of the group's position by resolving that only unclassified work —in which "free publication of the results cannot be restricted by the granting or contracting agency"—should be permitted at the university.

The president of the university, Gaylord P. Harnwell, has said that he regards the Senate action as being advisory rather than binding. The university administration is now considering a plan whereby classified projects would be moved to a private Science Center now being built near the university campus. The university is the largest stockholder in the Science Center, which has been designed to accommodate secret work. According to its executive vice-president, Jean Paul Mather, the center will provide "maximum security with minimum policing" for those who conduct such work. Mather observes that the Science Center will enable faculty members to continue classified investigations simply by "changing hats."

Jet Travel and Body Clocks

A series of tests carried out by the Federal Aviation Agency has substantiated the common complaint of air travelers that swift transition through several time zones disturbs their bodily and even their mental functions. The tests may result in changes of schedule for the crews on certain types of international flight. Moreover, the tests have implications for the proposal to build supersonic airplanes that would travel even faster than today's jets.

The tests involved healthy male volunteers, who were carried by jet airplane from the U.S. to such cities as Tokyo, Manila and Rome, passing through as many as 10 time zones. As a control to make sure that the effects resulted from changes of time and not merely from jet travel, there was a flight from Washington, D.C., to Santiago, Chile; it covered a long distance but was all in the same time zone. On the outbound flights that crossed a number of time zones the passengers underwent physiological changes—in heart rate, temperature and perspiration—that persisted for several days. They also showed a deterioration, for about a day, in mental acuity as indicated by difficulty in doing simple problems in arithmetic and by slowed responses to sensory stimuli. Similar effects appeared on the return trips but did not last as long. In contrast, the flight to Chile produced only a sense of fatigue.

The F.A.A. plans to give the tests to some pilots on the New York–Rome run in March. Sheldon Freud, an Air Force psychologist who has worked on the testing, said that the reaction of the passengers made it important to test the crews. "These men are responsible for the lives of millions of passengers every year," he said. Freud also raised a question about supersonic flights, which will be at least twice as fast as today's jet flights: "Will we have to rest twice as long afterward? Is it worth while getting over there in such a hurry?"

Dangerous LSD?

Indiscriminate and widespread use of the hallucinogenic drug d-lysergic acid diethylamide (LSD) has brought an increase in hospital admissions for adverse reactions to the drug, according to three psychiatrists at the New York University School of Medicine. Writing in *The New England Journal of Medicine,* William A. Frosch, Edwin S. Robbins and Marvin Stern report on 12 of the 27 patients treated for such reactions at Bellevue Psychiatric Hospital during a four-month period last year. All the patients had had some degree of personality difficulty before taking the drug; five were already "definitely psychotic." Their LSD-induced symptoms fell into three general categories: seven of them had acute panic reactions, three experienced reappearance of "drug" symptoms some time after having last taken LSD and three developed prolonged, overt psychoses. One man who was treated for panic was subsequently readmitted with a recurrence of symptoms.

According to the authors, panic is a common aspect of the LSD experience, but it rarely leads to hospitalization. The patients admitted with panic reactions all recovered quickly, but possible long-term effects have not been evaluated. Of the three recurrence cases, two patients experienced such LSD-induced symptoms as depersonalization and perceptual distortions a month or two after taking the drug; a third, who had been a heavy user of LSD but had not taken the drug for more than a year, kept having episodes of catatonia and hallucinations. All three were discharged after treatment but "were much more incapacitated than they had been before the LSD experience." As for the three patients who developed extended psychoses after a single experiment with LSD, they had all suffered from "extended schizophrenia" beforehand and had tried other drugs before LSD. At the time of admission one patient was paranoid and two were catatonic. Two were discharged after a month without marked improvement and a third had to be transferred for long-term treatment.

Frosch, Robbins and Stern suggest that LSD is now being ingested not only for "kicks" but also by anxiety-ridden people who think it will help them, in some cases as a substitute for psychotherapy. "Because of the widespread use of LSD," they write, "we hope that the deleterious effects will be evaluated in juxtaposition to the more optimistic claims of its enthusiasts."

The Omen of the Oxtail

The central religious rite of ancient Greece—animal sacrifice—is portrayed on thousands of vases and is prominent in Greek literature, but not much is known about it. One of the few concrete facts is that very little of the sacrifice was "received" by the divinity involved; the parts of the animal that ended up in the altar fire were mainly fat and bones. Intrigued by this custom, Michael H. Jameson of the Department of Classical Studies at the University of Pennsylvania recently undertook a survey of depictions of Greek sacrificial fires. Many of the vase paintings showed a peculiar curved object rising from the altar flames. This object had been variously interpreted in the past; modern scholars have generally agreed that it represents the sacrificed animal's tail or some other section of the vertebrae. It has not been apparent, however, what the object symbolizes, or whether it literally rose from the flames.

Jameson found a literary clue. In a comedy by Aristophanes a man making a sacrifice is asked, "How is the tail doing?" He replies, "It's doing fine." An ancient commentary on this passage explains that the Athenians perceived omens in the behavior of the tail. Jameson then decided to perform an experiment. He built an altar of concrete blocks in his backyard, bought an oxtail, put firewood on the altar and the tail on the firewood. After the fire had burned for a time he witnessed an unambiguously auspicious omen: the tip of the tail rose into the air and within 10 minutes duplicated the curvature of the object in the vase paintings. Jameson concludes that the Greek priests, having noticed this response of the animals' vertebral muscles to heat, found it convenient to tell their congregations that a rising tail was proof of a successful sacrifice.

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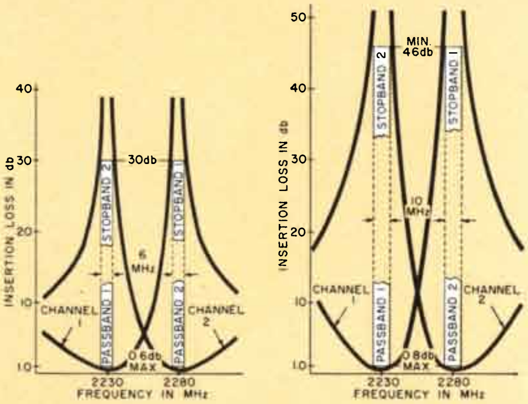

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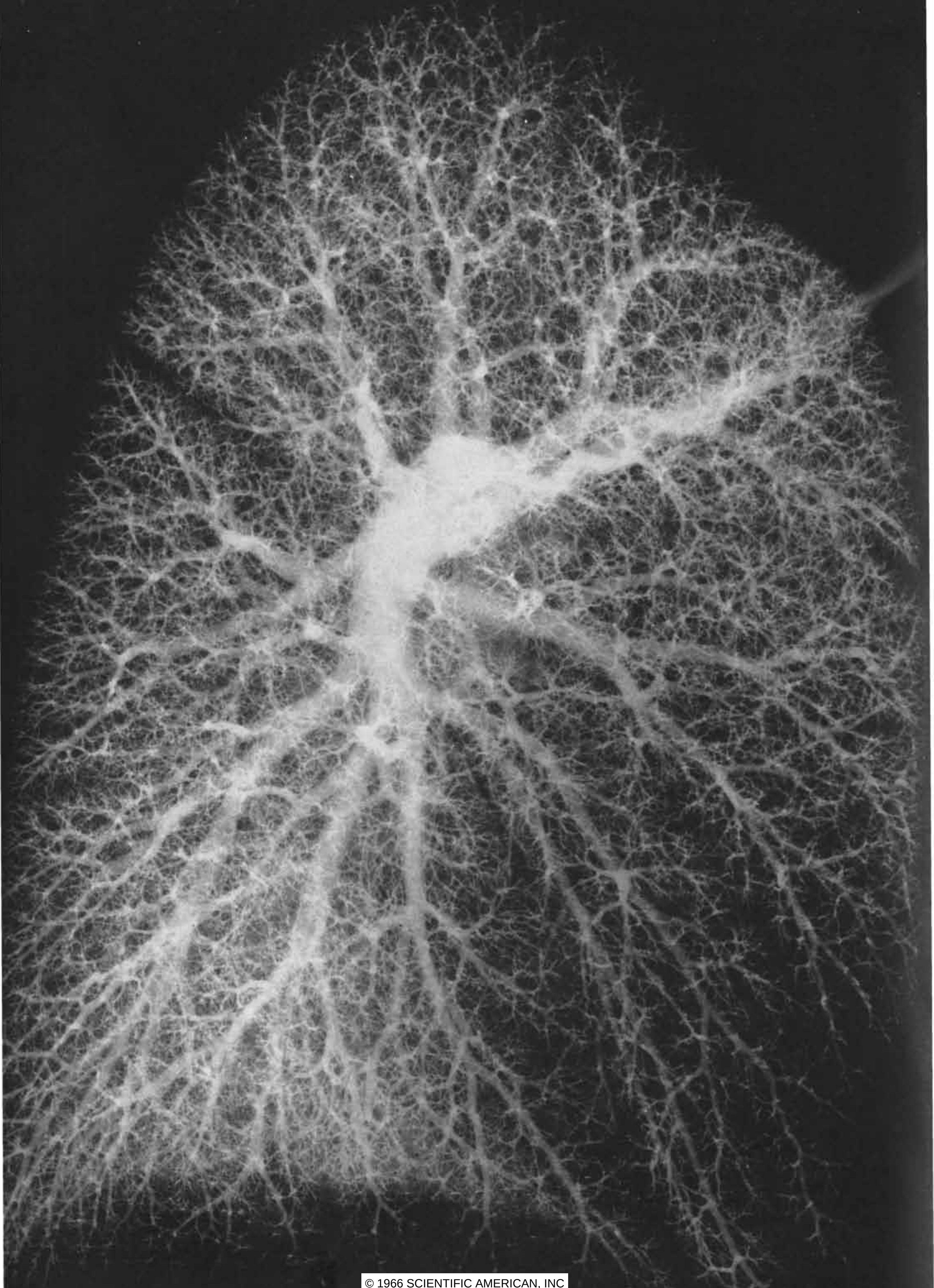


THE LUNG

This elaborately involuted tissue of air sacs and blood vessels serves to exchange gases between the air and the blood. In man the total area of the membrane between the two systems is 70 square meters

by Julius H. Comroe, Jr.

Each year an adult human inhales and exhales between two million and five million liters of air. Each breath consists of about half a liter of air, 20 percent of which is molecular oxygen (O_2); the air swirls briefly through a maze of branching ducts leading to tiny sacs that comprises a gas-exchange apparatus in which some of the oxygen is added to the blood. The apparatus I am describing is of course the lung: the central organ in the system the larger land animals have evolved as a means of supplying each of their cells with oxygen.

Oxygen is essential to most forms of life. A one-celled organism floating in water requires no complex apparatus to extract oxygen from its surroundings; its needs are satisfied by the process of diffusion—the random movement of molecules that results in a net flow of oxygen from regions of abundance to regions of scarcity. Over very short distances, such as the radius of a cell, the diffusion of oxygen is rapid. Over larger distances diffusion is a much slower process; it cannot meet the needs of any many-celled organism in which the distance between the source of oxygen and the most remote cell is greater than half a millimeter.

The evolution of large animals has therefore required the development of various special systems that deliver oxygen from the surrounding medium to each of the animal's cells. In higher vertebrates such as man this system consists of a gas pump (the thorax) and two fluid pumps (the right and left ventricles of the heart). The fluid pumps are linked to networks of capillaries, through the walls of which the actual exchange of gas molecules takes place. The capillary network that receives its blood from the left ventricle distributes oxygen throughout the body. The network that receives its blood from the right ventricle serves a different purpose. In it the actions of the fluid pump and the gas pump are combined to obtain the oxygen needed by the body from the surrounding atmosphere.

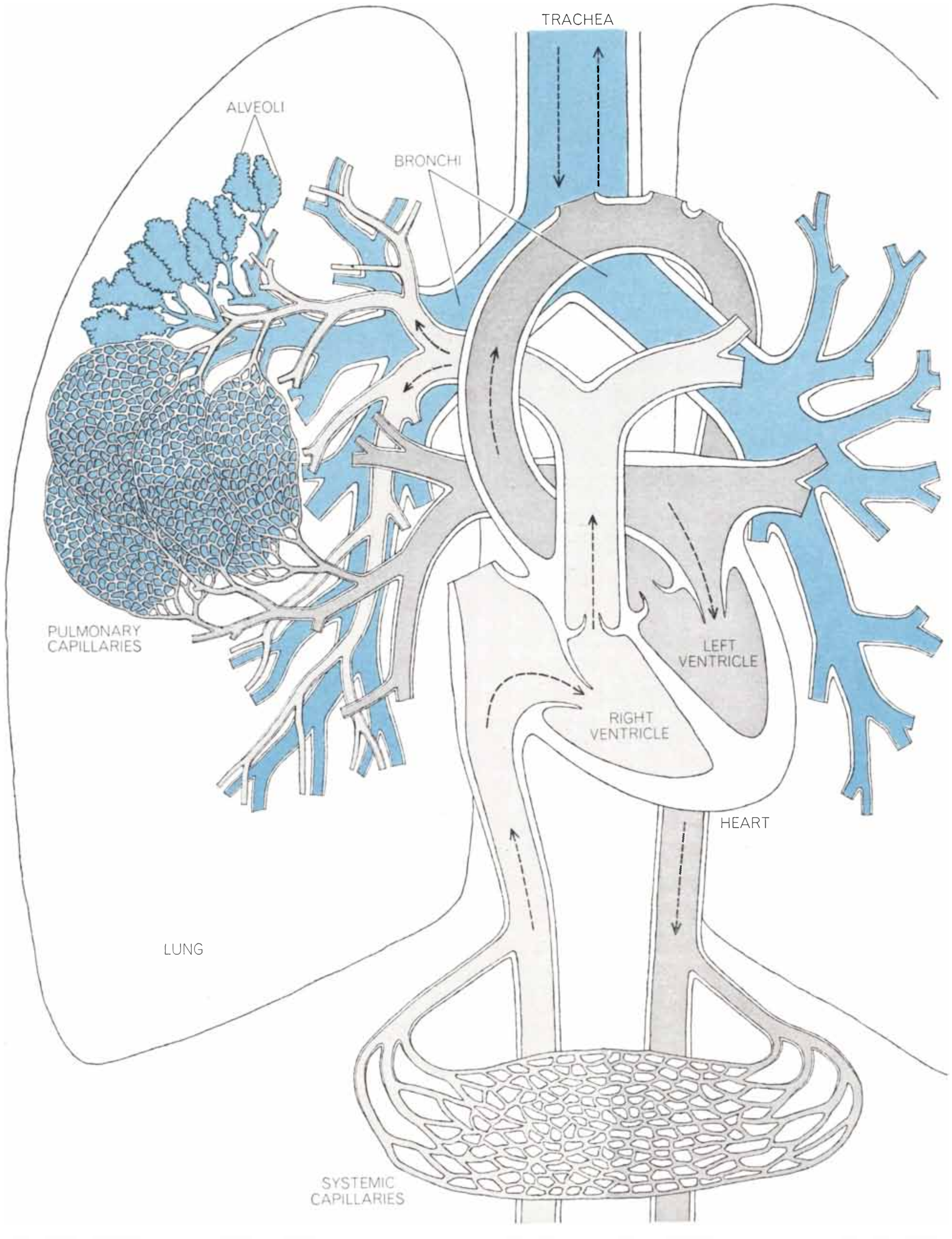
This integrated system works in the following manner. The expansion of the thorax allows air to flow into ducts that divide into finer tubes that terminate in the sacs called alveoli. The rhythmic contraction of the right ventricle of the heart drives blood from the veins through a series of vessels that spread through the lung and branch into capillaries [*see illustration on opposite page*]. These blood-filled pulmonary capillaries surround the gas-filled alveoli; in most places the membrane separating the gas from the blood is only a thousandth of a millimeter thick. Over such a short distance the molecules of oxygen, which are more abundant in the inhaled air than in the venous blood, diffuse readily into the blood. Conversely the molecules of the body's waste product carbon dioxide, which is more abundant in the venous blood than in the inhaled air, diffuse in the opposite direction. In the human lung the surface area available for this gas exchange is huge: 70 square meters—some 40 times the surface area of the entire body. Accordingly gas can be transferred to and from the blood quickly and in large amounts.

The gas exchange that occurs in the lungs is only the first in a series of events that meet the oxygen needs of the human body's billions of cells. The second of the two liquid pumps—the left ventricle of the heart—now distributes the oxygenated blood throughout the body by means of arteries and arterioles that lead to a second gas-exchange system. This second system is in reality composed of billions of individual gas-exchangers, because each capillary is a gas-exchanger for the cells it supplies. As the arterial blood flowing through the capillary gives up its oxygen molecules to the adjacent cells and absorbs the cells' waste products, it becomes venous blood and passes into the collecting system that brings it back to the right ventricle of the heart [*see illustration on next page*].

The customary use of the term "pulmonary circulation" for that part of the circulatory system which involves the right ventricle and the lungs, and of the term "systemic circulation" for the left ventricle and the balance of the circulatory system, seems to imply that the body has two distinct blood circuits. In actuality there is only one circuit; the systemic apparatus is one arc of it and the pulmonary apparatus is the other. The systemic part of the circuit supplies arterial blood, rich in oxygen and poor in carbon dioxide, to all the capillary gas-exchangers in the body; it also collects the venous blood, poor in oxygen and rich in carbon dioxide, from these exchangers and returns it to the right ventricle. The pulmonary part of the circuit delivers the venous blood to the pulmonary gas-exchanger and then sends it on to the systemic part of the circuit.

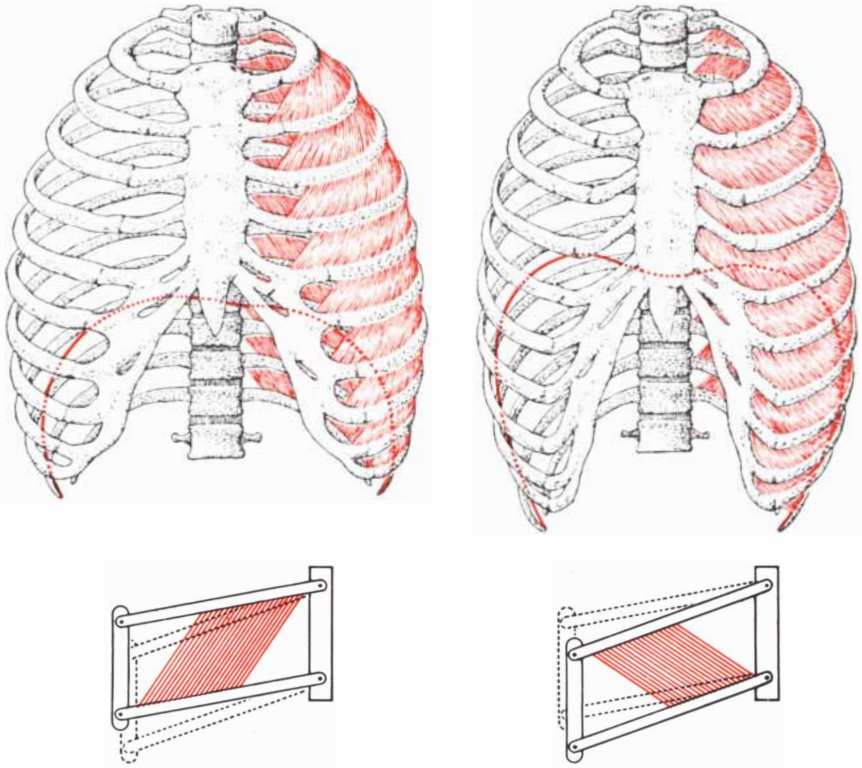
This combination of two functions not only provides an adequate exchange of oxygen and carbon dioxide but also

ARTERIAL SYSTEM of the human lung (*opposite page*) is revealed by X-ray photography following the injection of a radio-opaque fluid. The finest visible branches actually subdivide further into capillaries from five to 10 microns in diameter that surround the lung's 300 million air sacs.



THREE PUMPS operate the lungs' gas-exchange system. One gas pump, the thorax (*see illustration on opposite page*), moves from five to seven liters of air (*color*) in and out of the lungs' air sacs every minute. At top left these alveoli are shown without their covering of pulmonary capillaries, which are shown at center left. One fluid pump, the heart's right ventricle, forces from 70 to 100 cubic centimeters of blood into the pulmonary capillaries at each contraction. This blood (*light gray*) is low in oxygen and high in carbon dioxide; oxygen, abundant in the air, is diffused into the blood while carbon dioxide is diffused from the blood into the air. Oxygenated and low in carbon dioxide, the blood (*dark gray*) then reaches the third pump, the left ventricle, which sends it on to the systemic capillaries (*example at bottom of illustration*) that deliver oxygen to and collect carbon dioxide from all the body's cells.

supplies a variety of nutrients to the tissues and removes the products of tissue metabolism, including heat. Complex regulatory mechanisms ensure enough air flow and blood flow to meet both the body's overall needs and the special needs of any particular part of the body according to its activity.



INHALATION takes place when the thorax expands, thus forcing the lungs to enlarge and bringing the pressure of the gas within them below atmospheric pressure. The expansion (*top left*) is principally the work of the diaphragm but also involves the muscles of the rib cage (*detail at bottom left*). Exhalation occurs when passive relaxation reduces the size of the thorax (*top right*), thereby raising the gas in the lungs to greater than atmospheric pressure. Only under conditions of stress do muscles (*detail at bottom right*) aid exhalation.

The Respiratory System

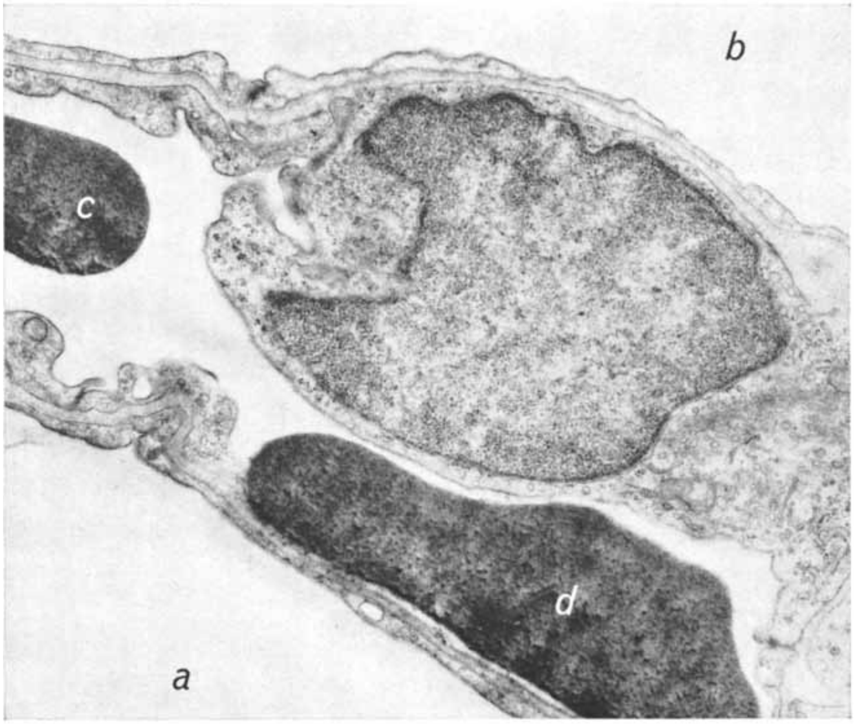
To the physiologist respiration usually means the movement of the thorax and the flow of air in and out of the lungs; to the biochemist respiration is the process within the cells that utilizes oxygen and produces carbon dioxide. Some call the first process external respiration and the second internal respiration or tissue respiration. Here I shall mainly discuss those processes that occur in the lung and that involve exchanges either between the outside air and the gas in the alveoli or between the alveolar gas and the blood in the pulmonary capillaries.

The structure of the respiratory system is sometimes shown in an oversimplified way that emphasizes only the conducting air path and the alveoli. The system is far more complex. It originates with the two tubes of the nose (the mouth can be regarded as a third tube), which join to become one: the trachea. The trachea then subdivides into two main branches, the right bronchus and the left. Each of the bronchi divides into two, each of them into two more and so on; there are from 20 to 22 bronchial subdivisions. These subdivisions give rise to more than a million tubes that end in numerous alveoli, where the gas exchange occurs. There are some 300 million alveoli in a pair of human lungs; they vary in diameter from 75 to 300 microns (thousandths of a millimeter). Before birth they are filled with fluid but thereafter the alveoli of normal lungs always contain gas. Even at the end of a complete exhalation the lungs of a healthy adult contain somewhat more than a liter of gas; this quantity is known as the residual volume. At the end of a normal exhalation the lungs contain more than two liters; this is called the functional residual capacity. When the lungs are expanded to the maximum, a state that is termed the total capacity, they contain from six to seven liters.

More important than total capacity, functional residual capacity or residual volume is the amount of air that reaches the alveoli. An adult human at rest inhales and exhales about half a liter of gas with each breath. Ideally each breath supplies his two-liter reservoir of gas—the functional residual capacity—with a volume of oxygen equal to the volume absorbed from the reservoir by the blood flowing through the pulmonary capillaries. At the same time each breath removes from the reservoir a volume of carbon dioxide equal to the volume produced by the body's cells and yielded to the lungs by the venous blood. The resting adult breathes from 10 to 14 times a minute, with the result that his ventilation—the volume of air entering and leaving the lungs—is from five to seven liters per minute. The maximum human capacity for breathing is about 30 times the resting ventilation rate, a flow of from 150 to 200 liters per minute. Even during the most intense muscular exercise, however, ventilation averages only between 80 and 120 liters per minute; man obviously has a great reserve of ventilation.

The volume of ventilation that is important in terms of gas exchange is less than the total amount of fresh air that enters the nose and mouth. Only the fresh air that reaches the alveoli and mixes with the gas already there is useful. Unlike the blood in the circulatory system, the air does not travel only in one direction. There are no valves in the bronchi or their subdivisions; incoming and outgoing air moves back and forth through the same system of tubes. Little or no gas is exchanged in these tubes. They represent dead space, and the air that is in them at the end of an inhalation is wasted because it is washed out again during an exhalation. Thus the useful ventilation obtained from any one breath consists of the total inhalation—half a liter, or 500 cubic centimeters—minus that part of the inhalation which is wasted in the dead space. In an adult male the wasted volume is about 150 cubic centimeters.

From an engineering standpoint this dead space in the air pump represents a disadvantage: more ventilation, which necessitates more work by the pump, is required to overcome the 30 percent inefficiency. The dead space may nonetheless represent a net advantage. The use of a single system of ducts for incoming and outgoing air eliminates the need for a separate set of ducts to carry each flow. Such a dual system would certainly encroach on the lung area available for gas exchange and might well result in more than a 30 percent inefficiency.



DIFFUSION PATH from gas-filled air sac to blood-filled capillary can be extremely short. In this electron micrograph of mouse lung tissue, *a* and *b* are air spaces; between these lies a capillary in which there are two red blood cells, *c* and *d*. The large light gray mass is the nucleus of an endothelial cell. The distances from air space *a* to red cell *d* and from air space *b* to red cell *c* are less than half a micron; the diffusion of gases across these gaps is swift.

Ventilation of the alveoli is not enough to ensure an adequate supply of oxygen. The incoming air must also be distributed uniformly so that each alveolus receives its share. Some alveoli are very close to the main branchings of the bronchi; others at the top and bottom of the lung are 20 or 30 centimeters away from such a branch. It is a remarkable feat of engineering to distribute the proper amount of fresh air almost simultaneously to 300 million alveoli of varying sizes through a network of a million tubes of varying lengths and diameters.

By the same token, ideal gas exchange requires that the blood be evenly distributed to all the pulmonary capillaries—that none of it should escape oxygenation by flowing through shunts in the capillary bed. Under abnormal circumstances, however, some alveoli are poorly ventilated, and venous blood flowing through the adjacent capillaries is not properly oxygenated. Conversely, there are situations when the flow of blood through certain capillaries is inadequate or nonexistent; in these cases good ventilation of the neighboring alveoli is wasted.

In spite of such deficiencies, the gas exchange can remain effective if the defects are matched (if the same regions that have poor ventilation, for example, also have poor blood flow), so that regions with increased ventilation also have increased blood flow. Two mechanisms help to achieve this kind of matching. First, a decrease in the ventilation of a group of alveoli results in a constriction of the blood vessels and a decrease in the blood flow of the affected region. This decrease is not the result of a nerve stimulus or a reflex but is a local mechanism, probably initiated by oxygen deficiency. Second, a local deficiency in blood flow results in a constriction of the pathways that conduct air to the affected alveoli. The resulting increase in airway resistance serves to direct more of the air to alveoli with a normal, or better than normal, blood supply.

The Pulmonary Circulation

The system that distributes blood to the lungs is just as remarkable as the system that distributes air. As I have noted, the right ventricle of the heart receives all the venous blood from every part of the body; the contraction of the heart propels the blood into one large tube, the pulmonary trunk. Like the trachea, this tube divides and subdivides, ultimately forming hundreds of millions of short, narrow, thin-walled capillaries. Each capillary has a diameter of from five to 10 microns, which is just wide enough to enable red blood cells to pass one at a time. The wall of the capillary is less than .1 micron thick; the capillary's length ranges from .1 to .5 millimeter.

If the pulmonary capillaries were laid end to end, their total length would be hundreds of miles, but the overall capillary network offers surprisingly little resistance to the flow of blood. In order to pump from five to 10 liters of blood per minute through the pulmonary system the right ventricle needs to provide a driving pressure of less than 10 millimeters of mercury—a tenth of the pressure required of the left ventricle for systemic circulation. With only a small increase in driving pressure the pulmonary blood flow can be increased to 30 liters per minute.

Although the total surface area provided by the pulmonary capillaries is enormous, at any instant the capillary vessels contain only from 70 to 100 cubic centimeters of blood. This volume is almost identical with the volume of blood the right ventricle ejects with each contraction. Thus with each heartbeat the reoxygenated blood in the pulmonary capillaries is pushed on toward the left ventricle and venous blood refills the capillaries. In the human body at rest each red blood cell remains in a pulmonary capillary for about three-quarters of a second; during vigorous exercise the length of its stay is reduced to about a third of a second. Even this brief interval is sufficient, under normal conditions, for gas exchange.

Electron microscopy reveals that the membrane in the lung that separates the gas-filled alveolus from the blood-filled capillary consists of three distinct layers. One is the alveolar epithelium, the second is the basement membrane and the third is the capillary endothelium. The cellular structure of these layers renders between a quarter and a third of the membrane's 70 square meters of surface too thick to be ideal for rapid gas exchange; over the rest of the area, however, the barrier through which the gas molecules must diffuse is very thin—as thin as .2 micron. Comparison of the gas-transfer rate in the body at rest with the rate during vigorous exercise provides a measure of the gas-exchange system's capacity. In the body at rest only 200 to 250 cubic centimeters of oxygen diffuse per minute; in the exercising body the system can deliver as much as 5,500 cubic centimeters per minute.

The combination of a large diffusion area and a short diffusion path is responsible for much of the lung's efficiency in gas exchange, but an even more critical factor is the remarkable ability of the red blood pigment hemoglobin to combine with oxygen. If plasma that contained no red cells or hemoglobin were substituted for normal blood, the adult human heart would have to pump 83 liters per minute through the pulmonary capillaries to meet the oxygen needs of a man at rest. (Even this assumes that 100 percent of the oxygen in the plasma is delivered to the tissues, which is never the case.) In contrast, blood with a normal amount of hemoglobin in the red cells picks up 65 times more oxygen than plasma alone does; the heart of a man at rest need pump only about five and a half liters of blood per minute, even though the tissues normally extract only from 20 to 25 percent of the oxygen carried to the cells by the red blood corpuscles.

The Mechanics of Breathing

Just as water inevitably runs downhill, so gases flow from regions of higher pressure to those of lower pressure. In the case of the lung, when the total gas pressure in the alveoli is equal to the pressure of the surrounding atmosphere, no movement of gas is possible. For inhalation to occur, the alveolar gas pressure must be less than the atmospheric pressure; for exhalation, the opposite must be the case. There are two ways in which the pressure difference required for the movement of air into the lungs can be created: either the pressure in the alveoli can be lowered below atmospheric pressure or the pressure at the nose and mouth can be raised above atmospheric pressure. In normal breathing man follows the former course; enlarging the thorax (and thus enlarging the lungs as well) enables the alveolar gas to expand until its pressure drops below that of the surrounding atmosphere. Inhalation follows automatically.

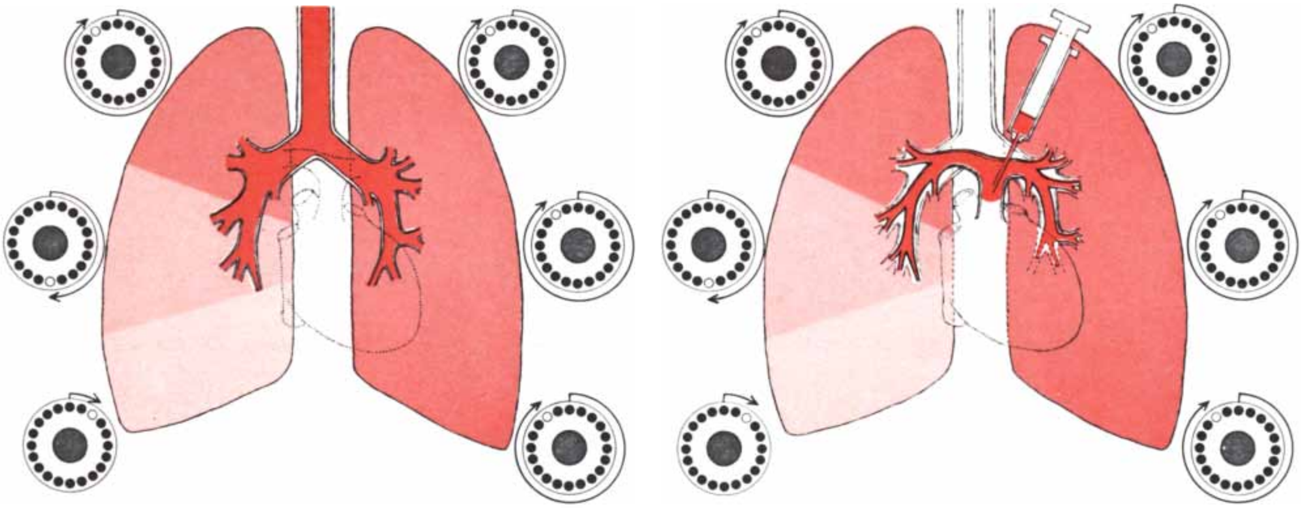
The principal muscle for enlarging the thorax is the diaphragm, the large dome-shaped sheet of tissue that is anchored around the circumference of the lower thorax and separates the thoracic cavity from the abdominal cavity. When the muscle of the diaphragm contracts, the mobile central portion of the sheet moves downward, much as a piston moves in a cylinder. In addition, skeletal muscles enlarge the bony thoracic cage by increasing its circumference [*see illustration on page 59*]. The lungs, of course, lie entirely within the thorax. They have no skeletal muscles and cannot increase their volume by their own efforts, but their covering (the visceral pleura) is closely linked to the entire inner lining of the thorax (the parietal pleura). Only a thin layer of fluid separates the two pleural surfaces; when the thorax expands, the lungs must follow suit. As the pressure of the alveolar gas drops below that of the atmosphere, the outside air flows in through the nose, mouth and tracheobronchial air paths until the pressure is equalized.

This kind of pulmonary ventilation requires work; the active contraction of the thoracic muscles provides the force necessary to overcome a series of opposing loads. These loads include the recoil of the elastic tissues of the thorax, the recoil of the elastic tissue of the lungs, the frictional resistance to the flow of air through the hundreds of thousands of ducts of the tracheobronchial tree, and the surface forces created at the fluid-gas interfaces in the alveoli [see "Surface Tension in the Lungs," by John A. Clements; SCIENTIFIC AMERICAN, December, 1962].

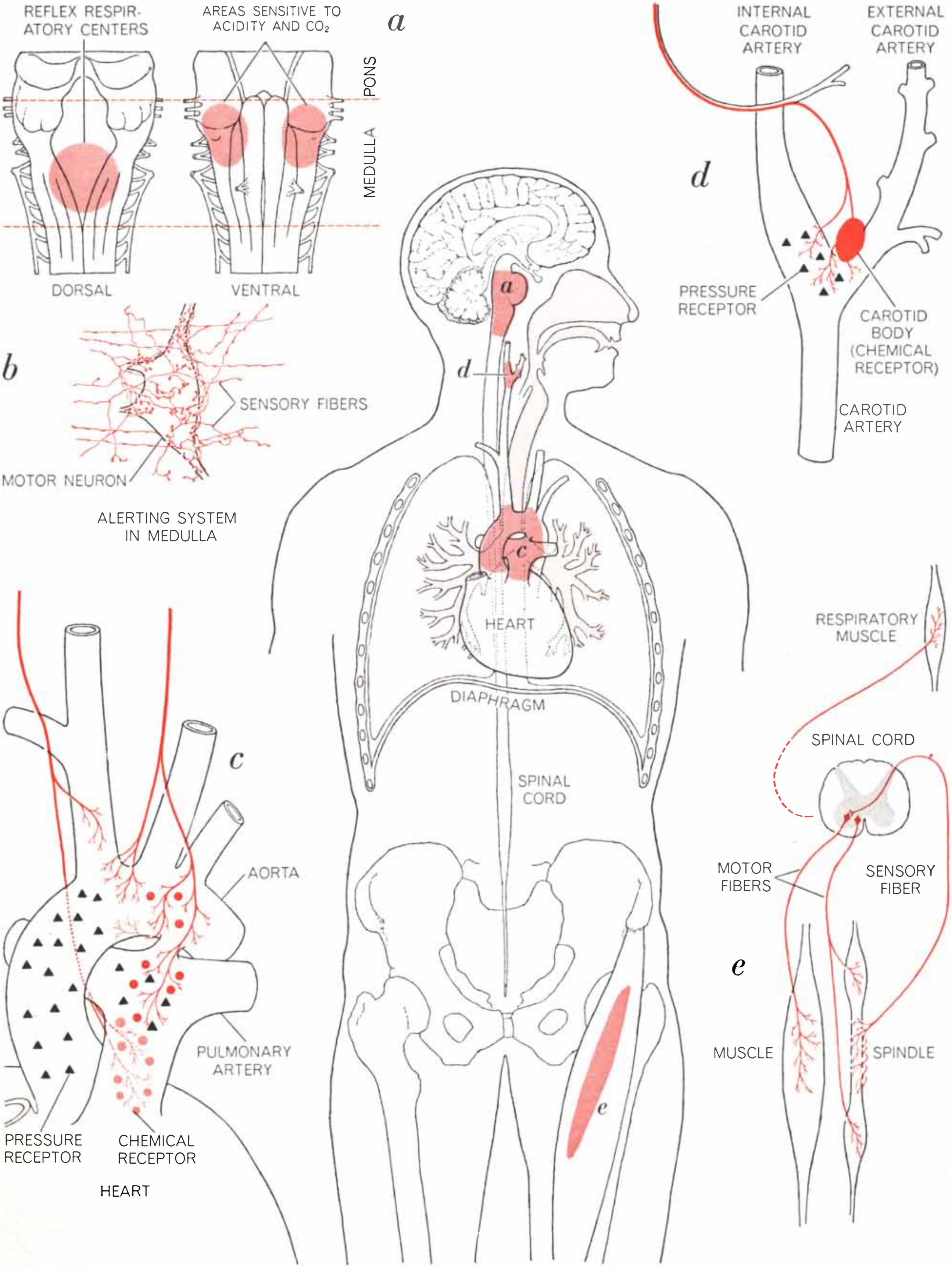
In contrast to inhalation, exhalation is usually a passive process. During the active contraction of muscles that causes the enlargement of the thorax, the tissues of thorax and lungs are stretched and potential energy is stored in them. The recoil of the stretched tissue and the release of the stored energy produce the exhalation. Only at very high rates of ventilation or when there is an obstruction of the tracheobronchial tree is there active contraction of muscles to assist exhalation.

Artificial ventilation can be produced either by raising external gas pressure or by lowering internal pressure. Body respirators of the "iron lung" type lower the pressure of the air surrounding the thorax in part of their cycle of operation. As a consequence the volume of the thorax increases, the alveolar pressure falls and, since the patient's nose and mouth are outside the apparatus, air at atmospheric pressure flows into his lungs. Later in the cycle the pressure within the respirator rises; the volume of the thorax decreases and the patient exhales.

Other types of artificial ventilation depend on raising the external pressure at the nose and mouth above the atmospheric level. Some mechanical respirators operate by supplying high-pressure



RADIOACTIVE TRACERS such as xenon 133 can assess the performance of the two components in the lungs' gas-exchange system. Inhaled as a gas (*left*), the xenon will be unevenly distributed if the air ducts are blocked; zones that are poorly ventilated will produce lower scintillation-counter readings than normal ones will. Injected in a solution into the bloodstream (*right*), the xenon will diffuse unevenly into the air sacs if the blood vessels are blocked. Such faulty blood circulation also causes low readings.



REGULATION OF BREATHING is controlled not only by the lower brain but also by a variety of other receptor and reflex centers. Portions of the pons and medulla of the lower brain (*a*) react to increases in acidity and carbon dioxide pressure. Other sensitive cells are attached to the aorta and pulmonary artery (*c*) and the carotid artery (*d*). The spindle receptors of skeletal muscles (*e*) also affect breathing, as do such external factors as temperature and vibration and such psychological ones as anxiety and wakefulness.

air at rhythmic intervals to the nose or mouth or more directly to the trachea. In mouth-to-mouth resuscitation the person who administers the air conveys it to the person who receives it by contracting his thorax and pushing air into the other person's lungs. Frogs can push air into their lungs by first filling their cheeks and then contracting their cheek muscles; some people whose respiratory muscles are paralyzed but whose head and neck muscles are not can learn to do this "frog breathing."

Still another way to increase the amount of oxygen available to human tissues is to place a hospital patient in an oxygen tent, in which the concentration of oxygen is increased, or to supply oxygen to him in a hyperbaric chamber, in which the total gas pressure is increased to two or three atmospheres. The extra oxygen that is taken up by the blood under these circumstances may be of help if the patient's clinical problem requires for its correction only more oxygen in the blood and tissues; such is the case, for example, when a patient has an infection caused by anaerobic bacteria. But supplying oxygen in greater than normal amounts does not increase ventilation and therefore cannot eliminate more carbon dioxide, nor does it increase the amount of blood being circulated. In the first instance, help in eliminating carbon dioxide is of prime importance in cases of pulmonary or respiratory disease; in the second, the tissues of patients with circulatory problems need not only more oxygen but also the added glucose, amino acids, lipids, white blood cells, blood platelets, proteins and hormones that can only be obtained from adequate blood flow.

The Measurement of Lung Function

Before the 1950's only a few tests of specific lung function had been devised. These included measurements of the amount of air in the lungs at the end of a full inhalation, the amount in the lungs at the end of a full exhalation, and the maximum amount exhaled after a full inhalation; these three volumes were known respectively as the total lung capacity, the residual volume and the vital capacity. In addition, some measurements had been made of the way in which gas was distributed throughout the tracheobronchial tree during inhalation by means of observing the dilution of a tracer gas such as helium or the exhalation of nitrogen following the inhalation of pure oxygen. Since the 1950's, however, pulmonary physiologists have developed a number of new instruments and test techniques with which to measure objectively, rapidly and accurately not only lung volume and the distribution and diffusion of gases but also the pulmonary circulation and the physical properties of the lung and its connecting air paths.

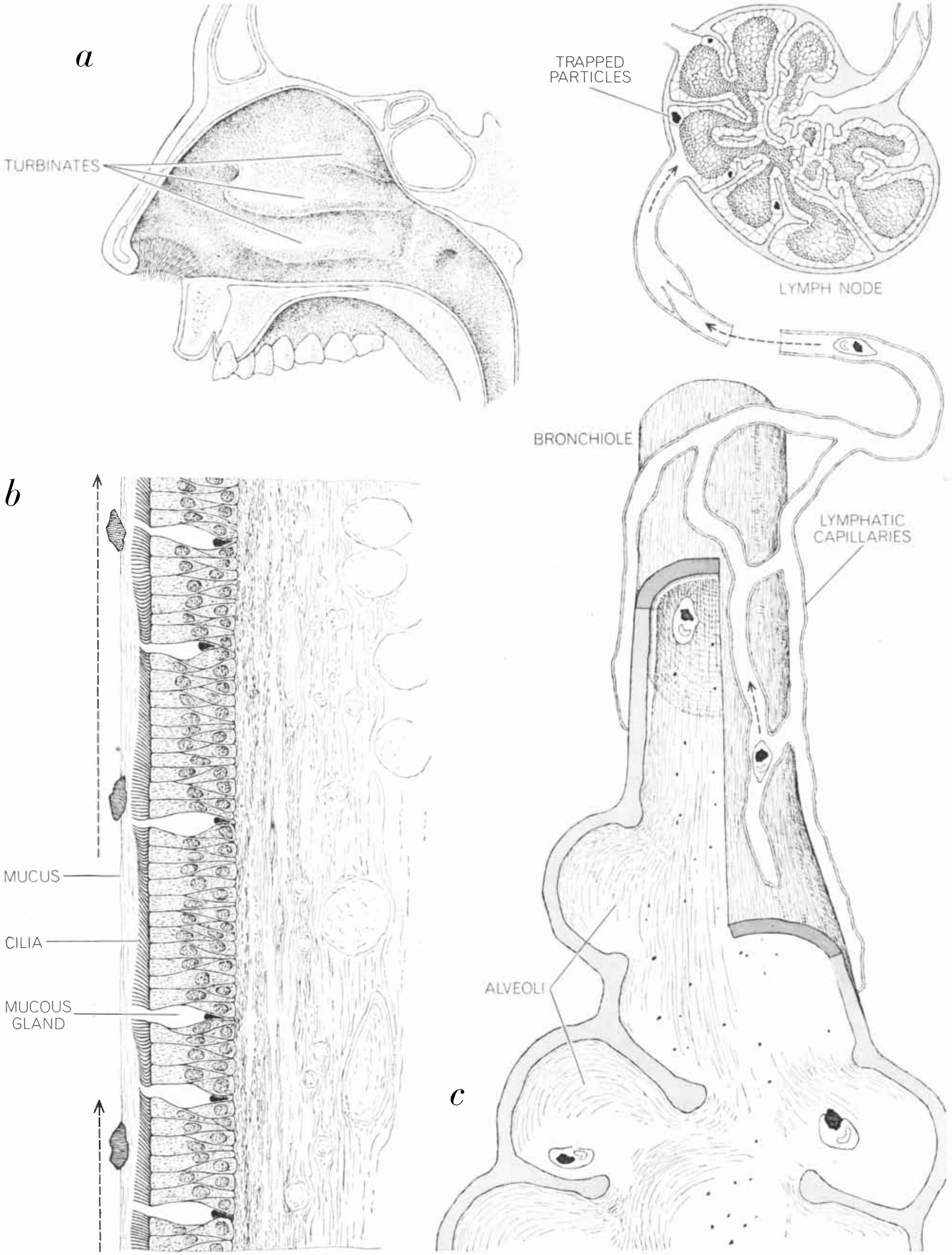
One such new instrument is the plethysmograph (also known as the body box), which can measure the volume of gas in the lungs and thorax, the resistance to air flow in the bronchial tree and even the blood flow in the pulmonary capillaries. For the first measurement the subject sits in the box (which is airtight and about the size of a telephone booth) and breathes the supply of air in the box through a mouthpiece fitted with a shutter and a pressure gauge. To measure the volume of gas in the subject's lungs at any moment an observer outside the box triggers a circuit that closes the shutter in the mouthpiece and then records the air pressure both in the subject's lungs and in the body box as the subject attempts to inhale; Boyle's law yields a precise measurement of the volume of gas in the subject's lungs.

In order to measure the blood flow in the pulmonary capillaries the subject in the body box is provided with a bag that contains a mixture of 80 percent nitrous oxide and 20 percent oxygen. At a signal the subject inhales a single breath of this mixture and holds the breath for a few seconds. Nitrous oxide dissolves readily in the blood; as its molecules diffuse from the alveoli to enter the blood flowing through the pulmonary capillaries, the total number of gas molecules in the alveoli obviously decreases. But the nitrous oxide that dissolves in the blood does not increase the volume of the blood; therefore the total gas pressure must decrease as the nitrous oxide molecules are subtracted. Knowing the total volume of gas in the lungs, the volume of nitrous oxide and the solubility of nitrous oxide in the blood, one can calculate the flow of blood through the pulmonary capillaries instant by instant. These calculations can be used both to measure the amount of blood pumped by the heart—and thus to arrive at an index of cardiac performance—and to detect unusual resistance to blood flow through the pulmonary capillaries.

To measure resistance to air flow in the bronchial tree the subject in the body box is instructed to breathe the air about him without any interruption while the observer continuously records changes in pressure in the box. One would expect that in a closed system the mere movement of 500 cubic centimeters of gas from the supply in the box into the lungs of a subject also in the box would not bring about any overall change in pressure. In actuality the pressure in the box increases. The reason is that gas can flow only from a region of higher pressure to a region of lower pressure. The subject cannot inhale unless the pressure of the gas in his lungs is lower than the pressure of the gas in the box; therefore the molecules of gas in his lungs during inhalation must occupy a greater volume than they did in the box before inhalation. The expansion of the subject's thorax, in turn, compresses—and thus is the equivalent of adding to—the rest of the gas in the body box; the effect is reversed as the thorax contracts during exhalation. An appropriately calibrated record of these pressure changes makes it possible for the pressure of the gas in the subject's alveoli to be calculated at any moment in the respiratory cycle. This test can be used to detect the increased resistance to air flow that arises in patients with bronchial asthma, for example, and to evaluate the effectiveness of antiasthmatic drugs.

Another useful instrument for the study of lung function is the nitrogen meter, developed during World War II by John C. Lilly at the University of Pennsylvania in order to detect leaks in or around aviators' oxygen masks. The instrument operates as an emission spectroscope, continuously sampling, analyzing and recording the concentration of nitrogen in a mixture of gases; its lag is less than a tenth of a second. Pulmonary physiologists use the nitrogen meter to detect uneven distribution of air within the lung. Assume that when one breathes ordinary air, the lungs contain 2,000 cubic centimeters of gas, 80 percent of which is nitrogen. If one next inhales 2,000 cubic centimeters of pure oxygen, and if this oxygen is distributed uniformly to the millions of alveoli, each alveolus should now contain a gas that is only 40 percent nitrogen instead of the former 80 percent. If, however, the 2,000 cubic centimeters of oxygen are not evenly distributed, some alveoli will receive less than their share, others will receive more, and the composition of the alveolar gas at the end of the oxygen inhalation will be decidedly nonuniform. In the alveoli that receive the most oxygen the proportion of nitrogen may be reduced to 30 percent; in those that receive little oxygen the proportion of nitrogen may remain as high as 75 percent.

It is impossible to put sampling



BAFFLE SYSTEM protects the lung's interior from intrusion by particles of foreign matter. Hairs in the nose and the convolutions of the turbinate bones (*a*) entrap most particles larger than 10 microns in diameter. Particles of from two to 10 microns in diameter usually settle on the walls of the trachea, the bronchi or the bronchioles, where the escalator action of mucus-covered cilia (*b*) carries them up to the pharynx for expulsion. Particles smaller than two microns in diameter reach the lung's air sacs (*c*). Some are engulfed by scavenger cells; others are carried to the nearest lymph node. Any that remain may cause fibrous tissue to form.

needles into thousands of alveoli in order to determine what mixture of gas each of them contains, but the nitrogen meter easily samples and analyzes the gas leaving the alveoli as the subject exhales. The first part of the exhaled gas comes from the outermost part of the tracheobronchial tree; it contains pure oxygen that has not traveled far enough down the conducting air path to mix with any alveolar gas. The second part of the exhalation shows a rapidly rising concentration of nitrogen; it represents alveolar gas that has washed some pure oxygen out of the conducting air path during exhalation and has mixed with it in the process. Once the conducting air path has been washed clear of oxygen, the remainder of the exhalation will be entirely alveolar gas. Analysis of the amount of nitrogen in the third part of the exhalation quickly shows whether or not the oxygen is distributed uniformly. If the distribution is uniform, the nitrogen-meter record for this part of the exhalation will be a horizontal line: from beginning to end the alveolar gas will be 40 percent nitrogen. If, on the other hand, the distribution is uneven, the nitrogen-meter record for the third part of the exhalation will rise continuously because the first part of the alveolar gas will come from well-ventilated areas of the lung and the last from poorly ventilated ones. In less than a minute the nitrogen meter can separate individuals with uneven ventilation from individuals whose ventilation is normal.

Having discovered by means of the nitrogen meter that a subject suffers from uneven ventilation somewhere in his lungs, the pulmonary physiologist can now use radioactive gases to determine exactly where the unevenness lies. The subject inhales a small amount of a relatively insoluble radioactive gas such as xenon 133 and holds his breath. A battery of three radiation counters on each side of the thorax measures the amount of radioactivity in the alveolar gas contained in the upper, middle and lower portions of each lung. Well-ventilated lung areas show a high level of radioactivity; poorly ventilated areas, a low level.

Radiation-counter readings can also be used to measure the uniformity of blood flow through the pulmonary capillaries. In order to do this the radioactive xenon is dissolved in a saline solution and the solution is administered intravenously. As it flows through the pulmonary capillaries the xenon comes out of solution and enters the alveolar gas. A high local concentration of xenon is an indication of a good flow of blood in that area; a low concentration indicates the contrary.

Another use of radioactive tracers to check on blood circulation involves the deliberate clogging of some fine pulmonary blood vessels. Radioactive albumin is treated so that it forms clumps that are about 30 microns in diameter—a size somewhat larger than the pulmonary capillaries or the vessels that lead into them. When the clumps are administered intravenously, they cannot enter blood vessels that are obstructed by disease; instead they collect in the parts of the lung with good circulation, where they block some of the fine vessels for a few hours. The whole thorax can now be scanned for radioactivity; in 10 or 20 minutes the activity of the albumin produces a clear image in which the regions of the lung with good pulmonary blood flow are clearly delineated.

Still another test, which measures the rate of gas exchange across the alveolar membrane, is made possible by the fact that hemoglobin has an extraordinary capacity for combining with carbon monoxide. The subject inhales a very low concentration of this potentially toxic gas. The carbon monoxide molecules diffuse across the capillary membranes and combine with the hemoglobin in the red blood cells. Assuming a normal amount of blood in the pulmonary capillaries, the rate at which the carbon monoxide disappears from the alveolar gas is directly proportional to its rate of diffusion. Unlike the somewhat similar test involving nitrous oxide, the carbon monoxide test measures only the rate of gas diffusion, not the rate of capillary blood flow. The affinity between the gas and the hemoglobin is so great that, even if the circulation of the blood were briefly halted, the stagnant red blood cells could still absorb carbon monoxide. A slow rate of carbon monoxide diffusion therefore indicates that the alveolar membranes have become thickened or that some abnormal fluid or tissue is separating many of the alveoli from the pulmonary capillaries.

The Regulation of Ventilation

The blood and air pumps that feed the lung's gas-exchange apparatus must be able to vary their performance to suit environments that range from sea level to high altitudes and activities that range from complete rest to violent exercise. Whatever the circumstances, exactly the right amount of oxygenated blood must be provided to meet the body's needs; to achieve this result responsive decision centers in the body, controlling both respiration and circulation, must not only be supplied with the necessary information but also possess the capacity to enforce decisions.

The first of these respiratory control centers was discovered by César Legallois of France in 1811. He found that if the cerebrum, the cerebellum and part of the upper brainstem were removed from a rabbit, the animal's breathing remained rhythmic, but that if a small region of the lower medulla was damaged or removed, breathing ceased. In the century and a half since Legallois' time physiologists have continued to accord this region of the brain—a group of interconnected nerve cells in the lower medulla—the paramount role in the control of respiration. This is not, however, the only region of the brain concerned with the regulation of breathing; there are chemically sensitive regions near the lateral surfaces of the upper medulla that call for an increase in ventilation when their carbon dioxide pressure or their acidity increases. Some other parts of the medulla, the cerebral cortex and the part of the brain called the pons can also influence respiration.

In addition to these areas in the brain a variety of respiratory receptors, interconnecting links, pathways and reflexes are found elsewhere in the body. Chemically sensitive cells in the regions of the carotid artery and the aorta initiate reflexes that increase respiration when their oxygen supply is not sufficient to maintain their metabolic needs or when the local carbon dioxide pressure or acidity increases. Stretch-sensitive receptors in the major arteries act through reflexes to increase or decrease respiration in response to low or high arterial blood pressure. Other receptors in the circulatory system, sensitive both to chemical stimuli and to mechanical deformation, can set off reflexes that slow or stop breathing. Respiration can also be regulated by the degree of inflation or deflation of the lungs, by the individual's state of wakefulness or awareness, by the concentration of certain hormones in the blood and by the discharge of the special sensory receptors known as spindles in skeletal muscles (including the respiratory muscles themselves).

We still do not know how some or all of these central and peripheral components interact to achieve the most important (and the most frequent) change in ventilation: the change that takes place when the body's metabolic activity increases. We know that during exercise both the body's oxygen consumption and its carbon dioxide production increase, and that so does the rate of ventilation. It is therefore logical to assume that ventilation is regulated by receptors somewhere in the body that are sensitive to oxygen or to carbon dioxide or to both. A puzzling fact remains: mild and even moderate exercise simply does not decrease the amount of oxygen or increase the amount of carbon dioxide in the arterial blood, yet the respiration rate rises. What causes this increase, which is enough to satisfy both the ordinary needs of the body and the extraordinary needs of exercising muscles? No one knows.

The Upper Respiratory Tract

In the course of taking from four to 10 million breaths a year each individual draws into the alveoli of his lungs air that may be hot or cold, dry or moist, possibly clean but more probably dirty. Each liter of urban air, for example, contains several million particles of foreign matter; in a day a city-dwelling adult inhales perhaps 20 billion such particles. What protects the lungs and the air ducts leading to them from air with undesirable physical characteristics or chemical composition? Sensory receptors in the air ducts and the lungs can initiate protective reflexes when they are suitably stimulated; specialized cells can also engulf foreign particles that have penetrated far into the lung. The main task of protecting the lungs, however, is left to the upper respiratory tract.

The nose, the mouth, the oropharynx, the nasopharynx, the larynx, the trachea and those bronchi that are outside the lung itself together constitute the upper respiratory tract. Although the obvious function of this series of passages is to conduct air to and from the lung, the tract is also a sophisticated air conditioner and filter. It contains built-in warning devices to signal the presence of most pollutants and is carpeted with a remarkable escalator membrane that moves foreign bodies upward and out of the tract at the rate of nearly an inch a minute. Within quite broad limits the initial state of the air a man breathes is of little consequence; thanks to the mediation of the upper respiratory tract the air will be warm, moist and almost free of particles by the time it reaches the alveoli.

The first role in the conditioning process is played by the mucous membrane of the nose, the mouth and the pharynx; this large surface has a rich blood supply that warms cold air, cools hot air and otherwise protects the alveoli under a wide range of conditions. Experimental animals have been exposed to air heated to 500 degrees centigrade and air cooled to −100 degrees C.; in both instances the trip through the respiratory tract had cooled or warmed the air almost to body temperature by the time it had reached the lower trachea.

The upper respiratory tract also filters air. The hairs in the nose block the passage of large particles; beyond these hairs the involuted contours of the nasal turbinate bones force the air to move in numerous narrow streams, so that suspended particles tend to approach either the dividing septum of the nose or the moist mucous membranes of the turbinates. Here many particles either impinge directly on the mucous membranes or settle there in response to gravity.

The filter system of the nose almost completely removes from the air particles with a diameter larger than 10 microns. Particles ranging in diameter from two to 10 microns usually settle on the walls of the trachea, the bronchi and the bronchioles. Only particles between .3 micron and two microns in diameter are likely to reach the alveolar ducts and the alveoli. Particles smaller than .3 micron, if they are not taken up by the blood, are likely to remain in suspension as aerosols and so are washed out of the lungs along with the exhaled air.

Foreign bodies that settle on the walls of the nose, the pharynx, the trachea, the bronchi and the bronchioles may be expelled by the explosive blast of air that is generated by a sneeze or a cough, but more often they are removed by the action of the cilia. These are very primitive structures that are found in many forms of life, from one-celled organisms to man. Resembling hairs, they are powered by a contractile mechanism; in action each cilium makes a fast, forceful forward stroke that is followed by a slower, less forceful return stroke that brings the cilium into starting position again. The strokes of a row of cilia are precisely coordinated so that the hairs move together as a wave. The cilia of the human respiratory tract do not beat in the open air; they operate within a protective sheet of the mucus that is secreted by glands in the trachea and the bronchi. The effect of their wavelike motion is to move the entire mucus sheet—and anything trapped on it—up the respiratory tract to the

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pharynx, where it can be swallowed or spat out.

The ciliary escalator is in constant operation; it provides a quiet, unobtrusive, round-the-clock mechanism for the removal of foreign matter from the upper respiratory tract. The speed of this upward movement depends on the length of the cilia and the frequency of their motion. Calculations show that a cilium that is 10 microns long and that beats 20 times per second can move the mucus sheet 320 microns per second, or 19.2 millimeters per minute. Speeds of 16 millimeters per minute have actually been observed in experiments.

In spite of all such preventive measures some inhaled particles—particularly those suspended in fluid droplets—manage to pass through the alveolar ducts and reach the alveoli. How do these deeper surfaces, which have no cilia or mucous glands, cleanse themselves? The amoeba-like lymphocytes of the bloodstream and their larger relatives the macrophages engulf and digest some particles of foreign matter. They can also surround the particles in the air ducts and then ride the mucus escalator up to the nasopharynx. Other particles may pass into lymphatic vessels and come to rest in the nearest lymph nodes. Some remain permanently attached to the lung tissue, as the darkened lungs of coal miners demonstrate. Many such intrusions are essentially harmless, but some, for example particles of silica, can result in the formation of tough fibrous tissue that causes serious pulmonary disease.

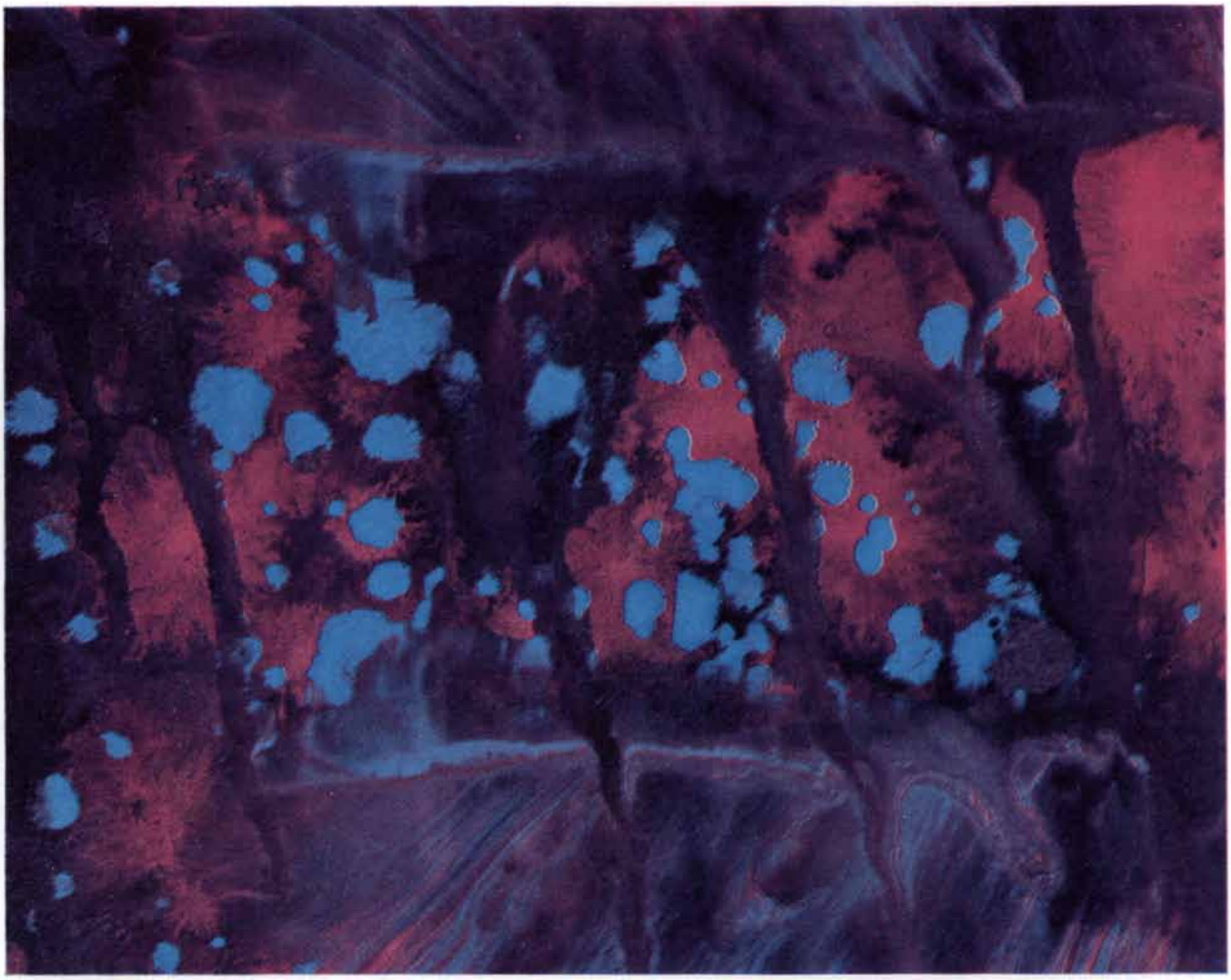
The filtration mechanism of the upper respiratory tract can thus be credited with several important achievements. It is responsible for the interception and removal of foreign particles. It can remove bacteria suspended in the air and also dispose of bacteria, viruses and even irritant or carcinogenic gases when they are adsorbed onto larger particles. Unless the filter system is overloaded, it keeps the alveoli practically sterile. This, however, is not the only protection the lungs possess. Among the reflex responses to chemical or mechanical irritation of the nose are cessation of breathing, closure of the larynx, constriction of the bronchi and even slowing of the heart. These responses are aimed at preventing potentially harmful gases from reaching the alveoli and, through the alveoli, the pulmonary circulation.

In many animals, for instance, the act of swallowing results in reflex closure of the glottis and the inhibition of respiration. Because the pharynx is a passageway both for air and for food and water, this reflex prevents food or water from entering the respiratory passages during the journey from the mouth to the esophagus. Because the reflex does not operate during unconsciousness it is dangerous to try to arouse an unconscious person by pouring liquids such as alcohol into his mouth.

When specific chemical irritants penetrate beyond the larynx, the reflex response is usually a cough combined with bronchial constriction. Like the swallowing reflex, the cough reflex is depressed or absent during unconsciousness. It also is less active in older people; this is why they are more likely to draw foreign bodies into their lungs.

Bronchial constriction is a response to irritation of the air paths that is less obvious than a cough. When the concentration of dust, smoke or irritant gas is too low to elicit the cough reflex, this constrictive increase in air-path resistance is frequently evident. Smoking a cigarette, for example, induces an immediate twofold or threefold rise in air-path resistance that continues for 10 to 30 minutes. The inhalation of cigarette smoke produces the same effect in smokers and nonsmokers alike. It does not cause shortness of breath, as asthma does; the air-path resistance must increase fourfold or fivefold to produce that effect. Nor has the reflex anything to do with nicotine; no increase in air-path resistance is caused by the inhalation of nicotine aerosols, whereas exactly the same degree of resistance is induced by smoking cigarettes with a normal (2 percent) or a minimal (.5 percent) nicotine content. The reflex is evidently triggered by the settling of particles less than a micron in diameter on the sensory receptors in the air path.

Other air pollutants—irritant gases, vapors, fumes, smokes, aerosols or small particles—may give rise to a similar bronchial constriction. It is one of the ironies of man's urban way of life that exposure to the pollutants that produce severe and repeated bronchial constriction results in excessive secretion of mucus, a reduction in ciliary activity, obstruction of the fine air paths and finally cell damage. These circumstances enable bacteria to penetrate to the alveoli and remain there long enough to initiate infectious lung disease. They are also probably a factor in the development of such tracheobronchial diseases as chronic bronchitis and lung cancer. Thus man's advances in material culture increasingly threaten the air pump that helped to make his evolutionary success possible.

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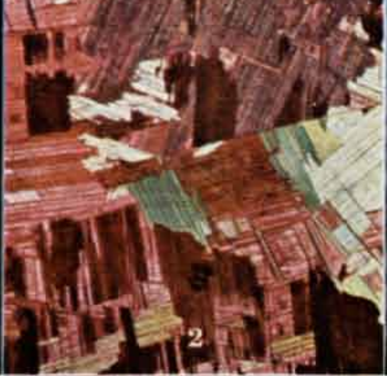
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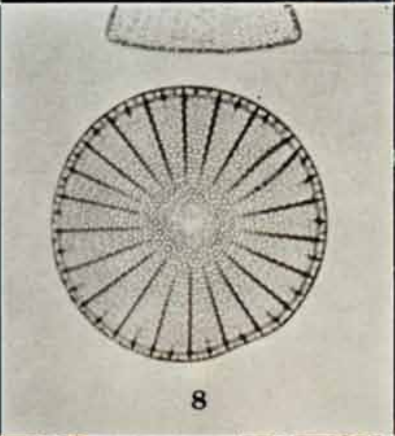
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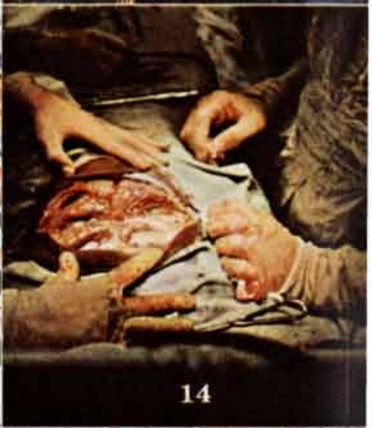
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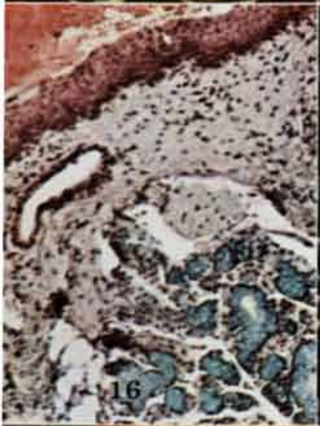
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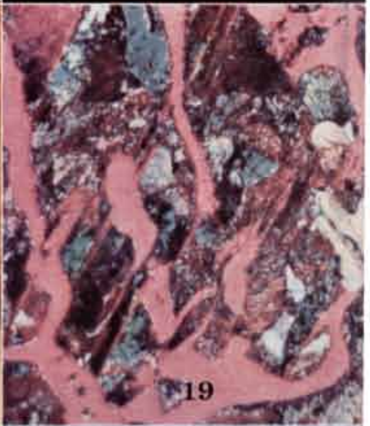
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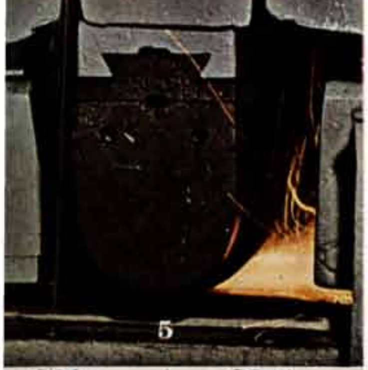
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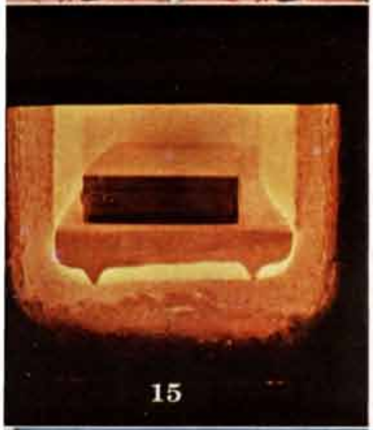
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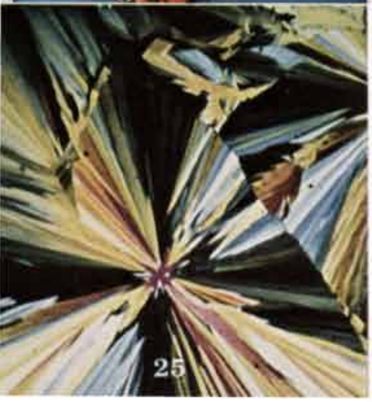
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1. Static test of a jet engine at AVCO's Research and Advanced Development Division.
2. Titanium dioxide magnified 200X under polarized light.
3. 10X macrophotograph (of a resistor) used in quality-control tests.
4. Illustration of an anemone for a garden catalog.
5. Automatic butt welder joining bimetallic strips into a continuous length.
6. Stress-analysis picture of plastic models under 80 psi pressure photographed in polarized light.
7. Illustration for a costume jewelry advertisement.
8. A diatom from Oamaru, New Zealand, magnified 100X.
9. *Carassius auratus.*
10. Employee identification picture (one exposure) made with an Avant QUAD Camera.
11. Fluorescence photomicrograph of a cross section of canine tibia, showing the site of active bone growth (69X).
12. Hardinge Super-Precision high-speed lathe.
13. Photomicrograph (100X) of differential staining of starch grains with vegetable dyes.
14. Pectus excavatum operation performed at Andrews Air Force Base Hospital.
15. Preliminary bonding of ingots in the forming of bimetallic strips at Metals and Controls Division of Texas Instruments.
16. Human larynx section (Trichrome stain) at 100X by Leo Goodman, Mallory Institute of Pathology.
17. Plasma-jet experiment used in high-temperature research.
18. Magazine illustration by advertising photographer, Wingate Paine.
19. White iron photographed at 400X under polarized light.
20. Gross specimen of a human gall bladder photographed at the Free Hospital for Women, Boston.
21. Research photomicrograph of a corrosion pit in cast bronze (50X).
22. Pre-flight check on an F-86 Sabrejet, Massachusetts ANG, 102nd Tactical Fighter Wing.
23. Proboscis of a *Calliphora* blowfly at a magnification of 100X.
24. Frictionless ruby bearing (with a gold-plated race) for a missile, 10X macrophotograph by New Hampshire Ball Bearing Co.
25. Beta bromopropionic acid crystals viewed between crossed polarizers (70X).

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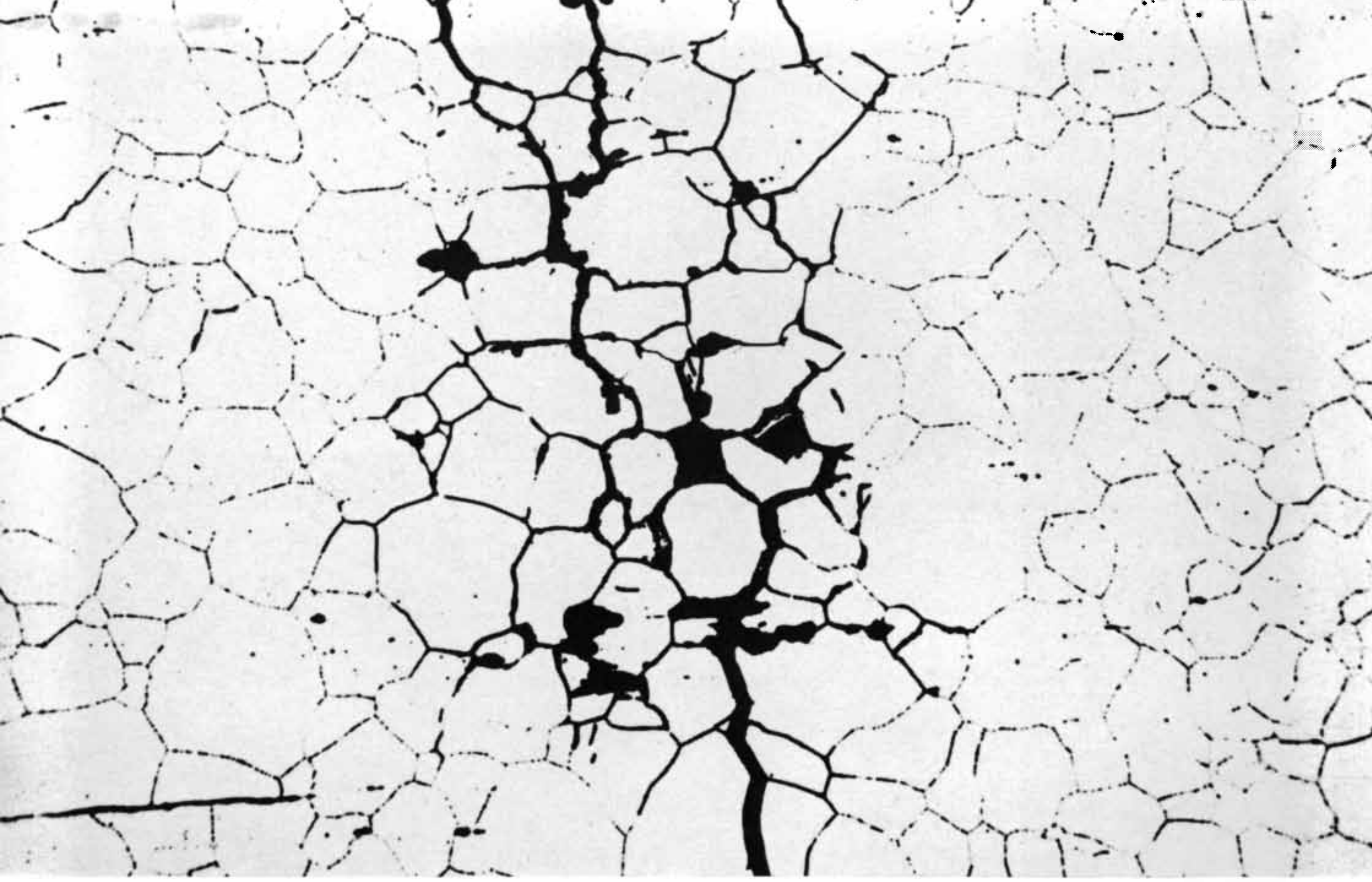
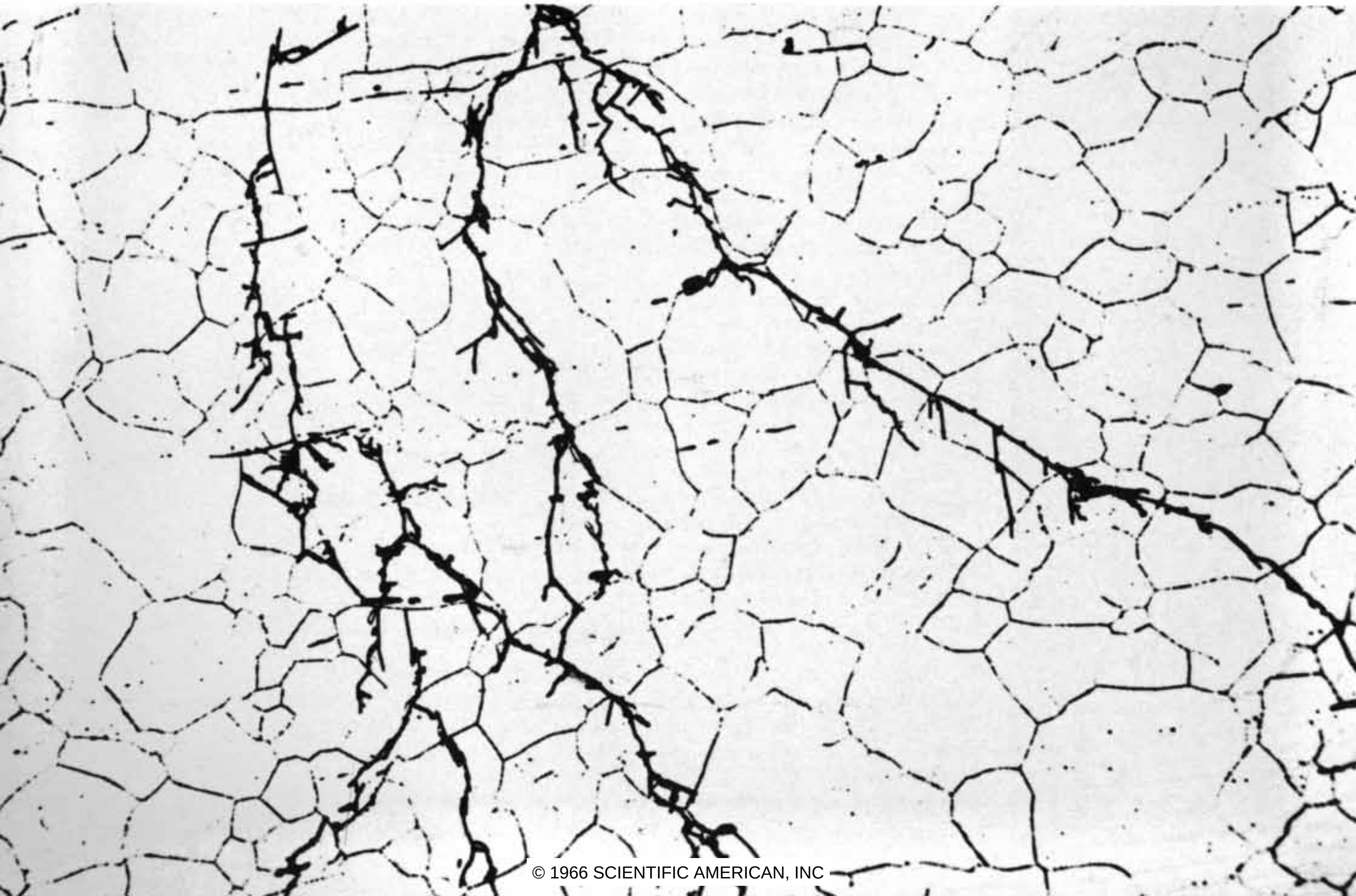


INTERGRANULAR CRACK caused by stress-corrosion appears as a network of heavy black lines running between the grains of a specimen of stainless steel in the photomicrograph above. The crack arises at the top. The specimen is enlarged 400 diameters.

TRANSGRANULAR CRACK also caused by stress-corrosion is similarly enlarged 400 diameters in the photomicrograph below. The crack's network of lines arises at the top of the micrograph and proceeds through interior of grains instead of between them.



STRESS-CORROSION FAILURE

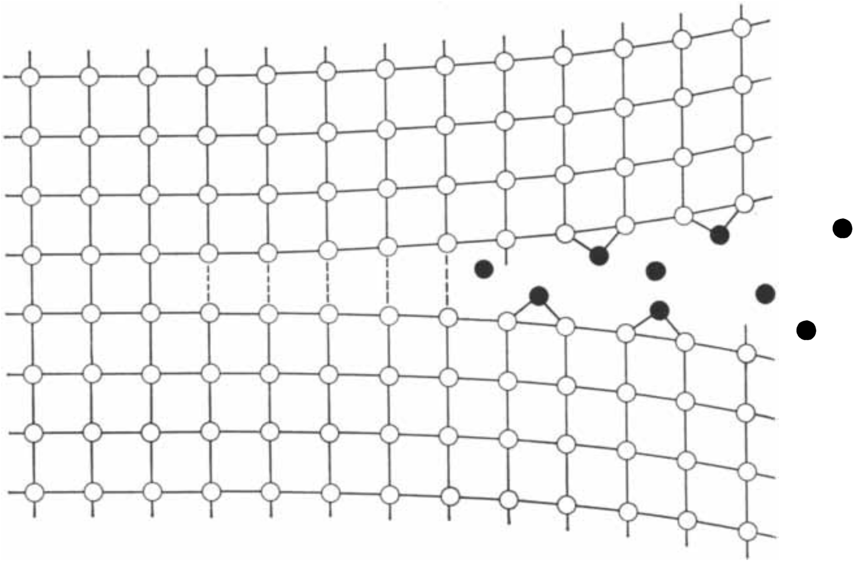
In some chemical environments alloys give way under stresses it was assumed they could bear. The importance of this phenomenon increases with the growing diversity of circumstances in which alloys are used

by Peter R. Swann

Men have come to stake their lives in many ways on the strength and reliability of metals. Occasionally, to our dismay, metal structures give way under stresses they were assumed to be able to bear. These sudden breakdowns can generally be traced to one of three causes: fatigue, which results from the repeated application of a relatively small stress; creep, a slow deformation that usually occurs at higher temperatures, and stress-corrosion failure, a weakness peculiar to alloys in some chemical environments. There are other types of failure caused by the incompatibility of a metal and its environment, but stress-corrosion failure is the most widespread and significant.

Incidents of stress-corrosion failure were first recorded in the 19th century by jewelers who observed that their cheaper gold alloys became brittle when exposed to certain solutions containing chloride ions. At the beginning of this century the phenomenon received wider notice when the brass cases of cartridges issued to the British army developed curious cracks on their arrival in India. Because the tendency to crack was greatest during the rainy season, the weakness was first known as "season" cracking. It was eventually shown that the cracking was caused by the combined action of traces of ammonia in the moist atmosphere and stresses remaining in the cartridge cases from the time of fabrication. If either the ammonia or the residual stresses were removed, the tendency to crack was eliminated. Once it was established that stress and a corrosive environment must act together to induce cracking, the more descriptive term "stress-corrosion" cracking was adopted. It is now known that stress-corrosion affects many alloys and has caused the explosion of boilers, the failure of aircraft parts and metal implants in the human body and costly breakdowns in nuclear reactors and chemical and manufacturing plants. The phenomenon is not restricted to metals; it occurs in plastics exposed under stress to some organic chemicals, and also in glasses subjected to stress in the presence of steam.

How does the environment of an alloy initiate a fracture and enable it to propagate even under a small stress? To this basic question can be added many others. Why are metals of high purity immune to stress-corrosion cracking? (In some cases only a few hundredths of 1 percent of impurity is required to make a metal susceptible.) Why do some environmental conditions cause cracking in one alloy and not in others? (Brasses, for example, fail when subjected to stress in the presence of ammonia, but copper-gold alloys do not.) Is the role played by corrosion essential to the failure? In many instances the degree of chemical attack from the environment is small, and sometimes no evidence of corrosion is visible to the unaided eye. Research into these questions has called for the application both of physical metallurgy (the study of mechanical properties such as strength and ductility) and electrochemistry (the relation of chemical changes to the flow of electricity). Ultimately both disciplines are concerned with the nature of events taking place on the atomic scale.

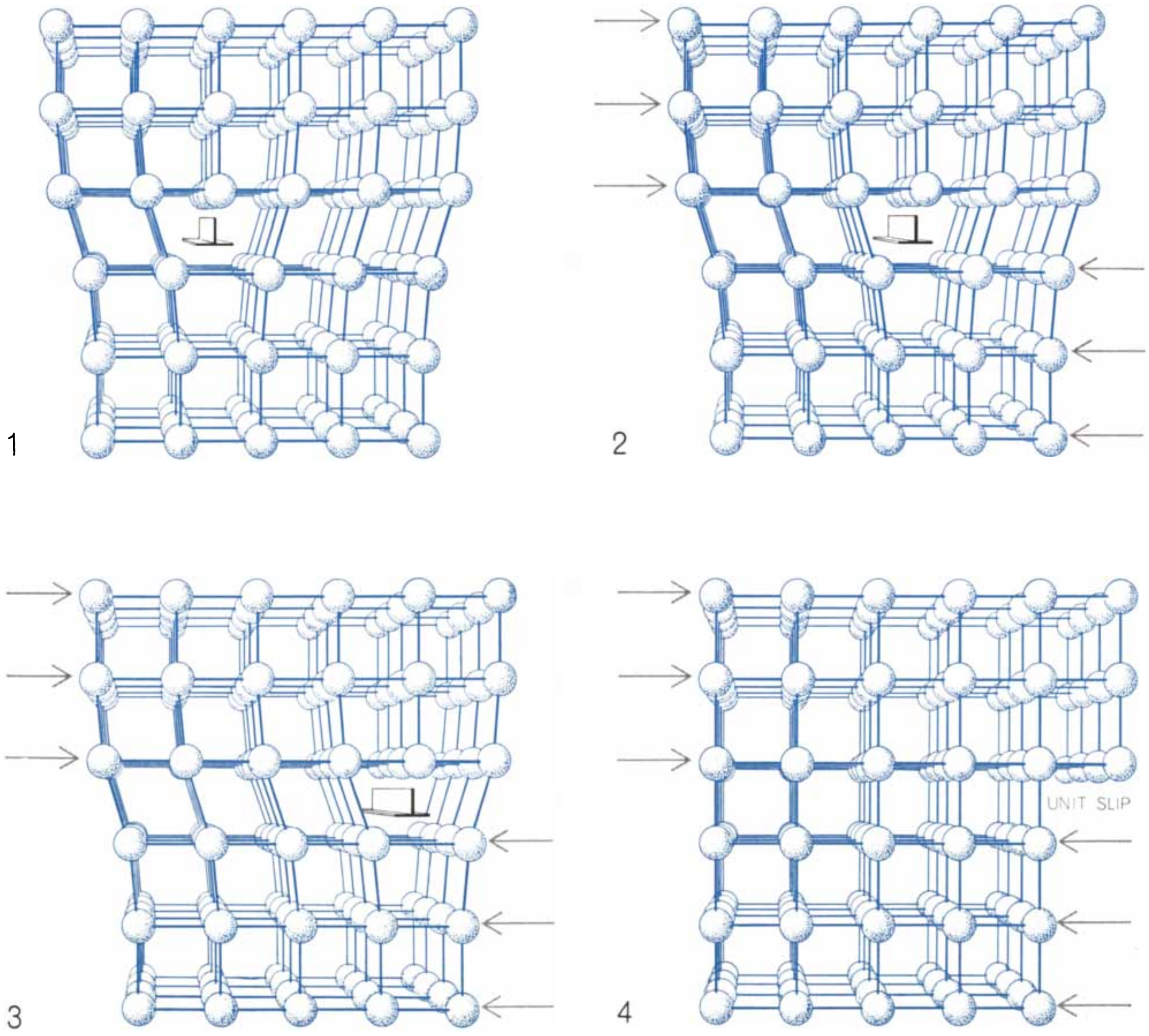


ATOMS AT TIP OF CRACK in a crystalline solid are represented schematically. One theory of stress-corrosion failure holds that certain ions from atmosphere (*black*) can penetrate to atoms at tip of crack and become strongly adsorbed, thus lowering the binding energy between these atoms and enabling the crack to propagate at an unusually low stress.

Although it is not usually obvious from their external shape, solid metals are crystalline; that is, their atoms are arranged in a regular three-dimensional array. In order to visualize how a crystalline structure would fracture we must consider the arrangements of atoms that would prevail at the tip, or leading edge, of a crack [*see illustration on preceding page*]. The atoms at the surface of the crystalline structure are not bonded on all sides, and consequently their energy is greater than the energy of the atoms inside the structure. This excess energy is termed surface energy. The atoms at the tip of the crack, which are displaced by the stress from their normal position, are in an intermediate energy state. Their excess energy is called elastic energy, and it can be increased to the level of surface energy by increasing the stress. A further increase in elastic energy will cause these atoms to move into positions characteristic of surface atoms and will allow the crack to advance a distance equivalent to the diameter of a few atoms.

The magnitude of the surface energy can be measured, and from it the value of the stress required to propagate the fracture can be calculated. This simplified method of determining the stress required for the propagation of a crack provides a somewhat low estimate because it does not take into account the fact that metals commonly undergo some plastic deformation before fracture. But even if we use the underestimated capacities of metals determined by this method, we find that stress-corrosion failure of an alloy ordinarily occurs at stresses of less than a hundredth of the load the alloy is assumed to be capable of sustaining.

How can fracture occur at so small a stress? One view is that the chemical environment has a considerable influence on the surface energy of the susceptible alloy. It is believed that cer-

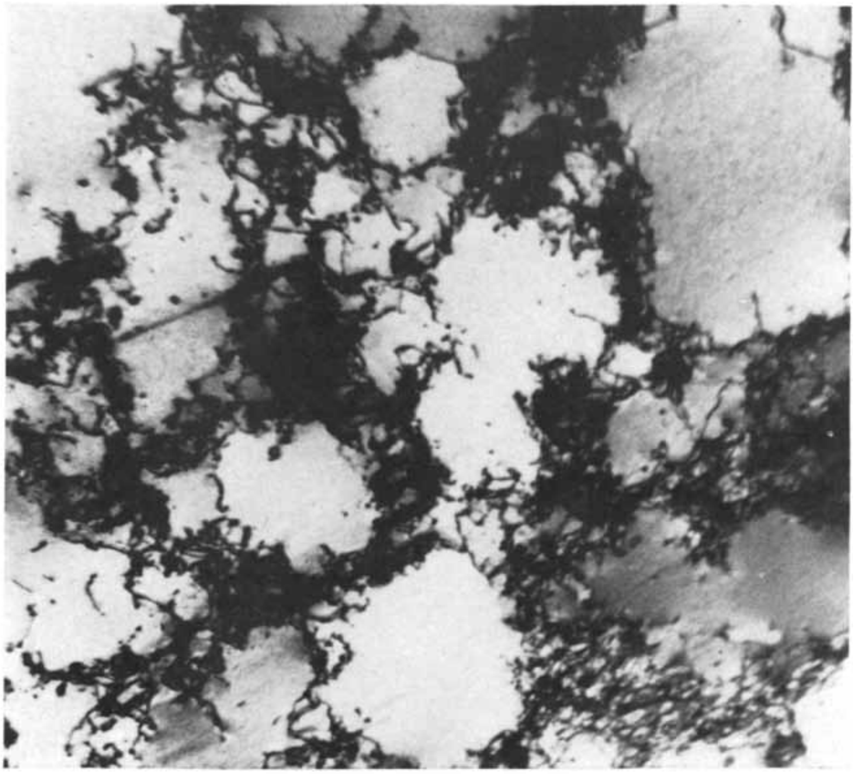


DISLOCATION is a defect involved in the stress-corrosion cracking of alloys. The edge dislocation, represented by the inverted *T*-shaped symbol, occurs where a plane of atoms is absent from the crystal lattice (*panel at top left*). When a small shearing force is applied, a simple flip in atomic bonding makes the dislocation jump one cell to the right (*top right*). Ultimately the dislocation reaches the edge of the crystal, producing a unit slip, or slip step. Plastic deformation of the metal involves many such slip steps in sequence.

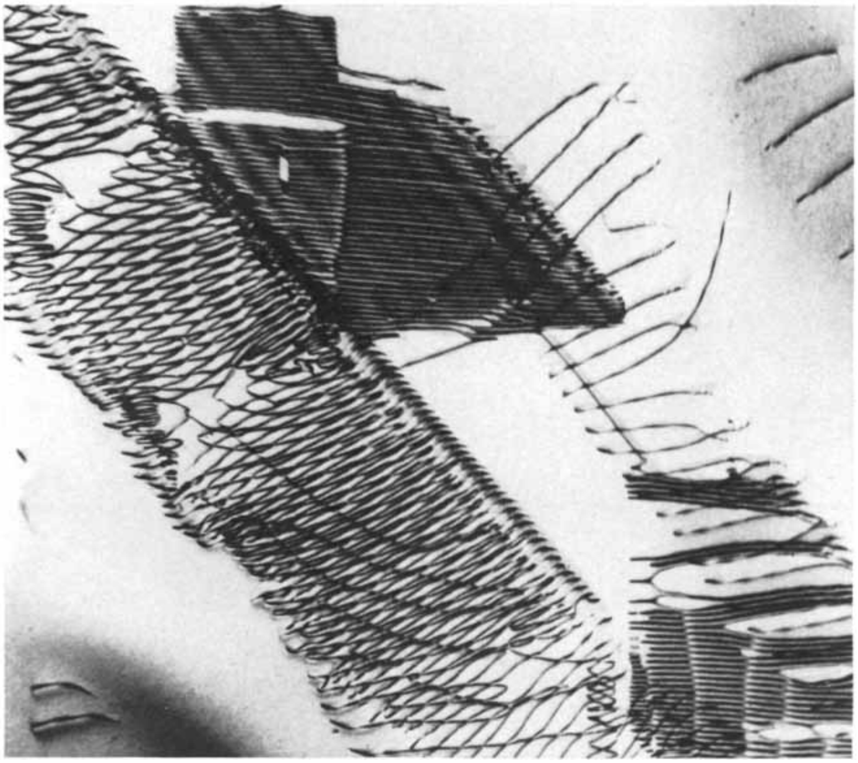
tain ions in the environment can diffuse to the tip of the crack and be adsorbed there and on the nearby walls. The adsorbed ions would lower the binding energy between surface atoms to the extent that crack propagation could occur at small stresses with little plastic deformation. This theory would explain the specific effectiveness of stress-corrosion environments. For any particular alloy only a few ions ordinarily present in the environment would be sufficiently small to diffuse to the tip of the crack (the radius of which would be on the order of the distance between the atoms of the alloy) and would also be capable of being adsorbed to the surface of the alloy. The theory holds up when it is applied to the environmentally induced fracture of nonmetals and to the cracking of pure metals and alloys in the presence of liquid metals. It does not explain, however, the very slow rates of stress-corrosion cracking in water solutions and the absence of such failure in pure metals.

A competing theory of stress-corrosion cracking proposes that fracture begins and proceeds with the electrochemical dissolution of the alloy along particularly reactive paths to form pits that eventually deepen into tunnels. The development of many corrosion tunnels would weaken the alloy so that a crack could be propagated by a small stress. One of the main premises of this theory is the existence of paths of enhanced reactivity throughout the susceptible alloy. After stress-corrosion failure occurs the path of a crack can be examined; often we find that the crack has followed the boundary between the adjoining grains, or small single crystals, that make up the metal. This intergranular fracture is readily explained. The distribution of elements in an alloy is not homogeneous, and the composition at or near a given grain boundary is different from the average composition of the alloy as a whole. Accordingly the chemical reactivity of the grain-boundary region is high.

In many alloys that are susceptible to stress-corrosion failure, however, the fracture path shows no preference for grain boundaries at all. In fact, stress-corrosion cracks can be produced in large single crystals of the susceptible alloys. This type of fracture, called transgranular fracture, is not so readily explained. Why do cracks propagate across the grains in some alloys? In an attempt to discover the nature of the transgranular paths the author, working under J. Nutting at the University of

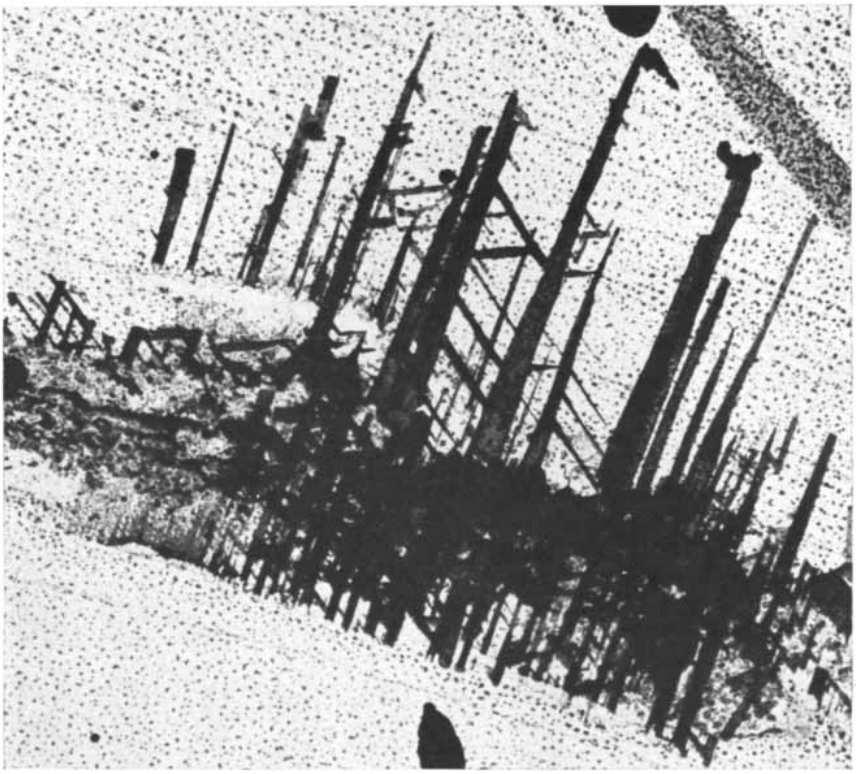


DISLOCATION "TANGLES" produced by deforming a specimen of pure copper are enlarged some 22,000 diameters in this electron micrograph. The image of an individual dislocation is some 50 atoms in width; in the micrograph each dislocation appears as a short dark line. The distribution of tangled dislocations is typical of pure metals and dilute alloys.



PLANE ARRAYS OF DISLOCATIONS is characteristic of their distribution in many concentrated alloys. This electron micrograph enlarges some 20,000 diameters the dislocations left after deformation of a concentrated copper alloy. The pattern suggests that during deformation groups of dislocations move one behind the other on well-defined planes.

CORROSION TUNNELS develop from pits on the surface of an alloy that elongate in the direction of closest atomic packing (*toward bottom right in this case*). Tunnels are some 250 atoms in diameter; this micrograph of an alloy enlarges them some 100,000 diameters.



LININGS OF TUNNELS, the needle-like objects in this micrograph, were made to cling to an oxide replica of a stainless-steel surface while the alloy in which they had formed was selectively dissolved. The micrograph was made by N. A. Nielsen at the Experimental Station of E. I. du Pont de Nemours and Company in Wilmington, Del. It indicates that corrosion tunnels are nucleated (that is, they form initially) in rows on the surface of the alloy.

Cambridge and later with Howard Pickering and David Embury at the Edgar C. Bain Laboratory for Fundamental Research of the United States Steel Corporation in Monroeville, Pa., employed the technique of transmission electron microscopy to examine susceptible alloys at magnifications large enough to resolve most crystal defects.

This technique involves reducing the specimen to a thickness of about 500 atoms. Electrons accelerated to high velocities can then be caused to penetrate the specimen and make visible the defects in the crystal lattice. The kind of defect of immediate interest to us is called a dislocation. Such a defect is created when one part of a crystal is displaced with respect to the rest [*see illustration on page 74*]. The boundary of the region that slips—the dislocation line—can be made to move over a crystal plane (called a slip plane) by the action of an external stress. The growth of the slipped region is complete when the dislocation line passes through the crystal surface to form a step. It is the motion of dislocations that allows a metal to be deformed in a ductile manner, but since the slip associated with each dislocation is only of atomic dimensions, the motion of billions of dislocations per cubic inch of metal is needed to produce even a slight plastic deformation. Fortunately for investigators of metals a dislocation is visible in a micrograph made with the electron microscope because the distorted crystal lattice near the axis of the dislocation diffracts the illuminating electron beam more strongly than the undistorted crystal that surrounds it. The dislocation thus appears as a thin dark line.

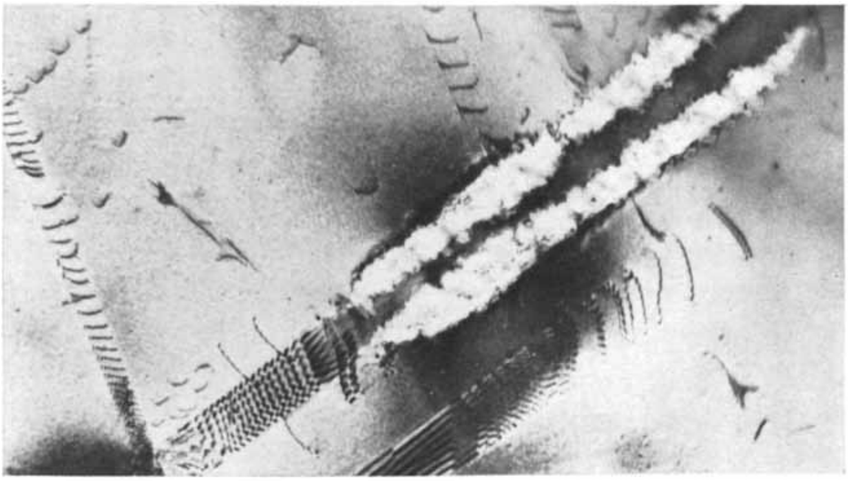
Our initial experiments compared the structure of deformed copper alloys of different composition. Specifically we sought to determine why dilute alloys—that is, alloys containing relatively little of the alloying element or elements—do not show transgranular cracks when they fail by stress-corrosion, whereas the more concentrated alloys do. In some of the electron micrographs we made we observed a striking effect of the concentration of the alloying element (or elements) on the distribution of dislocations in copper alloys. At a low concentration the dislocations form tangles with a cellular configuration; at a concentration high enough for transgranular stress-corrosion cracks to occur the dislocations move one behind the other in groups on well-defined planes [*see bottom illustration on preceding page*]. Apparently transgranular cracks are formed only when the deformation takes place in this way.

The correlation of groups of dislocations in planes and the formation of transgranular cracks has been found to apply to many alloys susceptible to stress-corrosion failure. One such alloy of iron, which contains chromium, nickel and small but important amounts of nitrogen and carbon, is a stainless steel with a useful property: its crystal structure changes when the alloy is cooled to the temperature of liquid air. The room-temperature form, called austenite, is susceptible to transgranular cracking in a solution of boiling saturated magnesium chloride, but the low-temperature form, called martensite, does not fail in the presence of this solution. By slowly lowering the temperature we can obtain a specimen of this stainless steel that is partially transformed from austenite to martensite; thus we can directly compare the distribution of dislocations in the austenite and martensite structures. The dislocations of the martensite structure do not form in planes, but dislocations in the austenite structure do. Since no local changes in chemical composition can occur during the low-temperature transformation from austenite to martensite, it is clear that susceptibility to stress-corrosion cracking depends on some physical characteristic of the susceptible alloy.

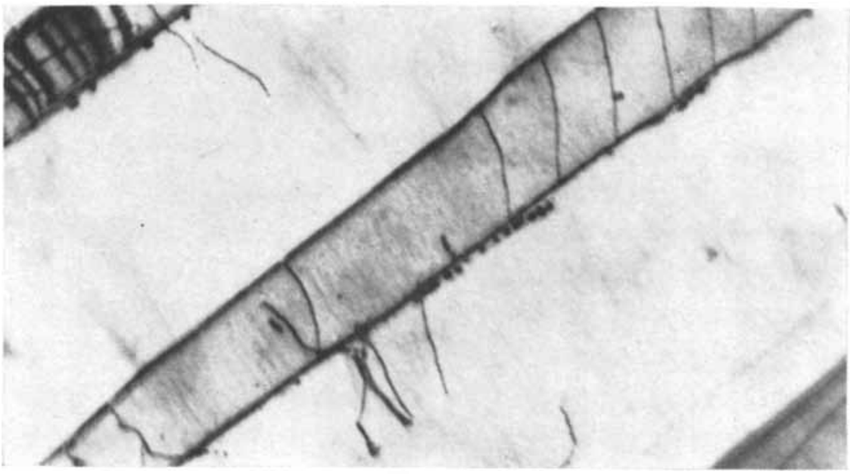
These early experiments led us to suppose that the plane groups of dislocations might themselves provide the reactive path in cases of transgranular cracking. To test this idea we exposed specimens of various alloys to stress in corrosive environments, so that we could observe with the electron microscope the first stage of chemical attack. To our disappointment the plane groups of dislocations were not attacked preferentially; instead attack occurred randomly over the surface of the susceptible alloys, taking the form of pits that ranged from 20 to 500 atoms in diameter. The pits continued to grow in the direction of the most closely spaced atoms of the crystal structure, elongating into tunnels. The rate at which the tunnels developed was quite high; it was comparable to the known rate at which cracks propagate during stress-corrosion failure.

Corrosion tunnels have also been revealed in electron micrographs made by N. A. Nielsen of the Experimental Station of E. I. du Pont de Nemours and Company in Wilmington, Del. Nielsen

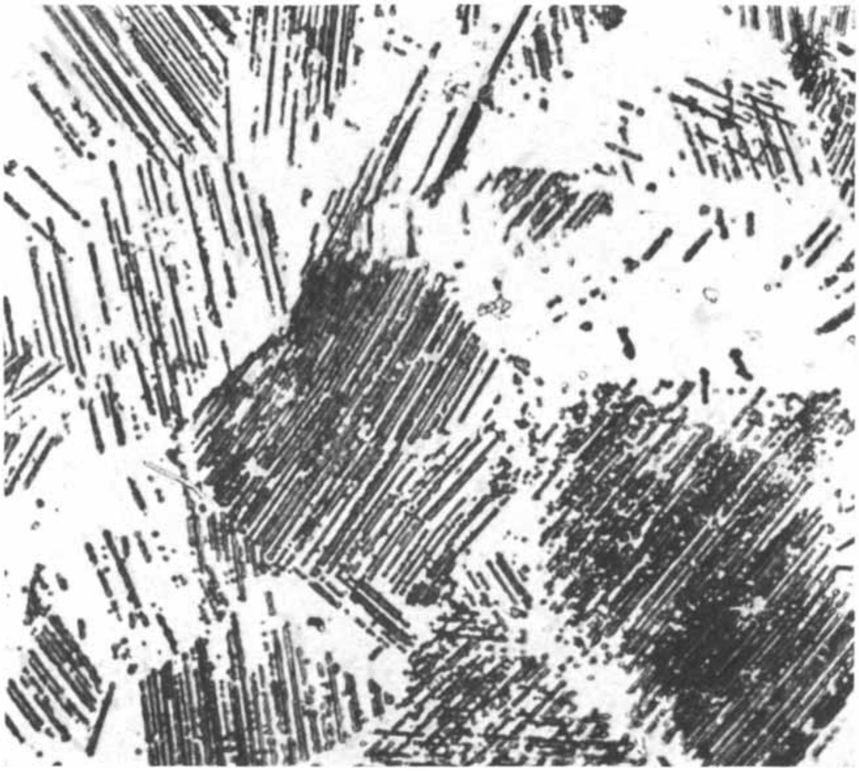
EARLY EFFECT OF CORROSION, the formation of pits (*rows of black dots*), is shown directly on the surface of a stainless steel. The dislocations (*black lines*) create slip steps that serve as nuclei for pits. The slip steps themselves cannot be seen in this micrograph.



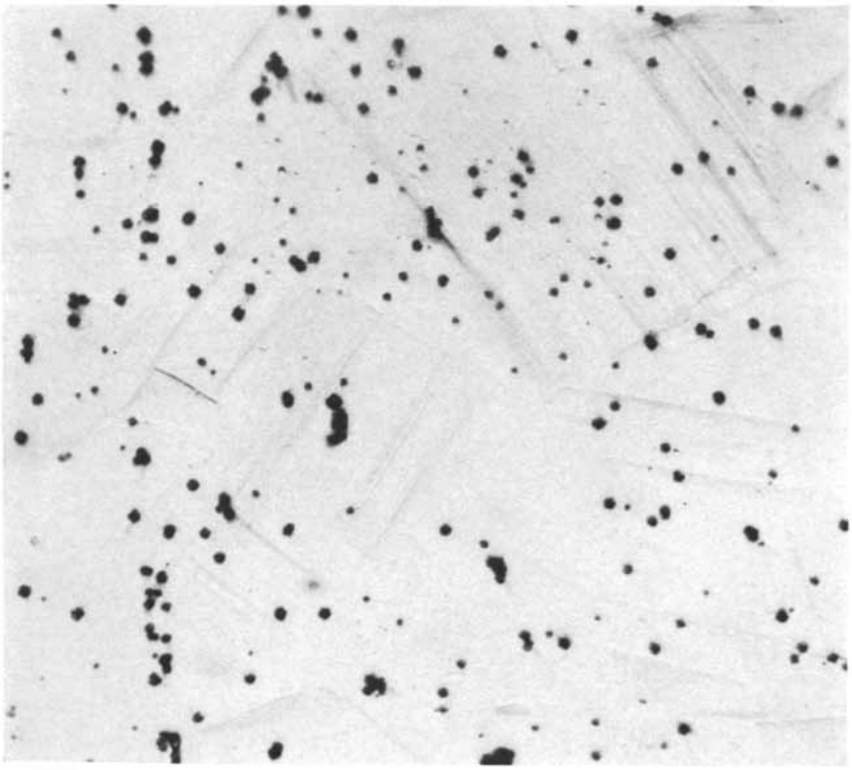
FINAL EFFECT OF CORROSION on a thin specimen of alloy is a slot that pierces it. Corrosion slots are formed by tunnels merging; two appear in this micrograph (*white regions*).



SLIP TRACES, the paths made by movement of dislocations, appear as long dark lines and dislocations as short vertical lines in this micrograph. A stressed alloy was immersed in a solution that liberated tiny particles of platinum (*black dots*) when it decomposed. The presence of these particles near the slip traces indicates an area of enhanced reactivity.



UNPROTECTED SURFACE of a freshly deformed stainless-steel specimen was exposed to a solution that decomposed so as to liberate platinum particles at the chemically active slip steps (*straight dark lines*). Slip steps in any grain of the alloy are approximately parallel.

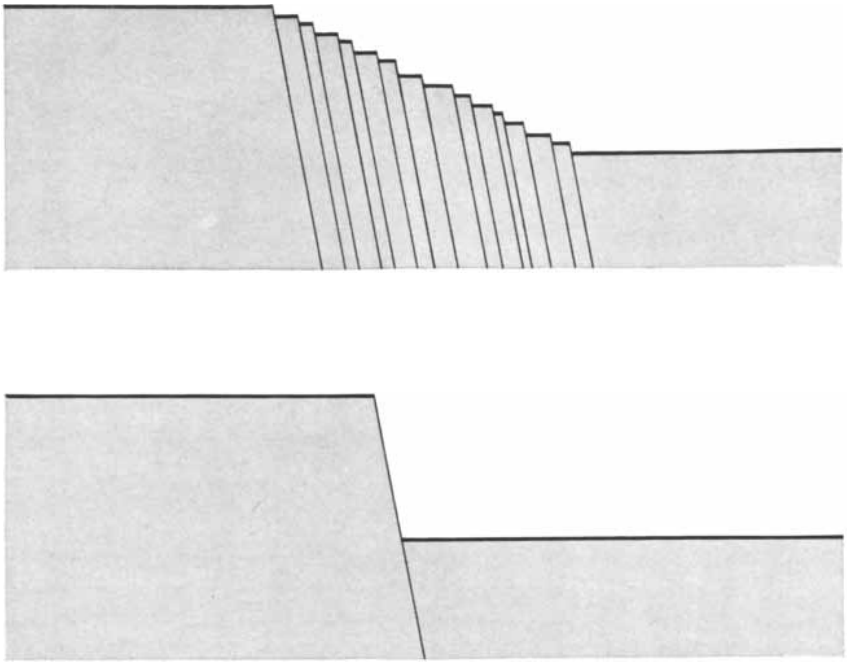


PROTECTED SURFACE of a stainless-steel specimen that had been deformed before it was immersed and stressed in a solution known to cause stress-corrosion failure was also exposed to a solution that liberated platinum particles. These deposited in a random way rather than near the slip steps. It appears that only newly formed slip steps are chemically reactive.

developed a technique for examining stress-corrosion cracks in stainless steels that involves oxidizing the surface of the corroded specimen and then dissolving the underlying metal. This procedure leaves an oxide replica of the surface, approximately 200 atoms thick, to which any corrosion products would adhere. The linings of the tunnels are of course corrosion products, and so Nielsen was able to isolate them and make micrographs of them. They appeared as long, hollow threads sticking out of the oxide replica [*see bottom illustration on page 76*]. The tunnels themselves were judged to have formed initially on some defect in the crystal structure, and the direction of their growth seemed to be related to the crystal lattice of the alloy. Nielsen's pictures also showed for the first time a definite link between the corrosion tunnels and the stress-corrosion crack itself. In one of his micrographs a network of corrosion tunnels can be seen in front of a region in which the tunnels had grown together to form a transgranular crack.

The precise nature of the defects that provide nuclei, or points of formation, for the corrosion tunnels cannot be determined from oxide replicas of the alloy surface. This can best be done by experimenting with thin films of the alloy itself. In our laboratory we have stressed alloy specimens for a few seconds in a boiling saturated solution of magnesium chloride and then examined them in the electron microscope for signs of chemical attack. At the earliest stage of nonrandom attack discernible to us the nuclei of corrosion tunnels appear as horizontal rows of black dots. It is important to note that the nuclei of the corrosion tunnels are not provided by the dislocation lines themselves but by the slip steps they have created on the top and bottom surfaces of the thin specimen. Several examples of corrosion pits more than 100 atoms deep were observed along slip steps after only a few seconds of exposure to the stress-corrosion environment. One micrograph we obtained illustrates the final stage of crack formation, in which the pits have grown together and completely penetrated the thin specimen. This micrograph helped to dispel our notion that the tunnel is nucleated at the plane groups of dislocations; clearly nucleation occurs at the traces of slip planes on the surface.

The sites where the dissolution of the alloy actually begins can best be revealed by a technique of platinum "dec-



PROTECTIVE FILM on the surface of an alloy such as a stainless steel can be broken in one of two ways, depending on the distribution of the shear (that is, the type of slip). Fine slip (*top*) exposes a much smaller area of underlying metal than coarse slip (*bottom*).

oration" that was originally used by Nielsen in conjunction with his surface-replica technique. This method exploits the fact that ions of chloroplatinic acid will decompose on the surface of an alloy adjacent to regions in which the metal is being dissolved. The tiny particles of platinum liberated when this decomposition occurs can be detected in the electron microscope because they strongly scatter the electrons in the illuminating beam. When the platinum-decoration technique is applied to stressed thin specimens, the chemical activity of the slip steps is demonstrated plainly. One can thus observe in the same electron micrograph slip traces (paths made by the movement of dislocations in thin alloy specimens), the dislocations that produced them and the particles along the slip step [*see bottom illustration on page 77*].

Our proposal that slip steps provide nuclei for stress-corrosion cracks was apparently in conflict with the experimental observation that the density of surface slip steps is often 100 to 1,000 times greater than the density of stress-corrosion cracks. This discrepancy was explained, however, by another experiment involving stainless steels. Stainless steels would be very reactive alloys if it were not for a thin surface film, chemically inert to most environments, that forms when such steels are exposed to air. This film prevents further corrosion and gives the steels their stainless qualities. It seems safe to assume, in working with stainless steels, that the traces along which corrosion tunnels form are precisely those sites where the protective film has been broken by the formation of slip steps.

Two stainless-steel specimens were electropolished to give them similar surfaces and then were deformed under stress to produce surface slip steps. The first specimen was immersed for one minute in a boiling saturated solution of magnesium chloride that had been "doped" with chloroplatinic acid to help reveal the chemically active sites on the surface of the specimen. Using a light microscope, we observed the expected result: crystals of platinum deposited along the surface slip steps in the various grains of the alloy [*see top illustration on opposite page*]. The second specimen was immersed in an undoped magnesium chloride solution for one minute, after which it was transferred to the doped solution for another one-minute immersion. We observed that the prior immersion in undoped magnesium chloride solution eliminated the enhanced reactivity of the slip steps; they ceased to be preferred sites of platinum decoration [*see bottom illustration on opposite page*]. We concluded from this experiment that the damage to the surface film resulting from the slip steps produced by deformation is rapidly repaired during exposure to the boiling magnesium chloride solution. Whether dissolution can continue once nucleation takes place must depend on the rate of film repair compared with the rate of film breakdown caused by the motion of dislocations. Consequently it appears that only slip steps that are created during exposure to the cracking solution have the potential of nucleating and propagating stress-corrosion cracks.

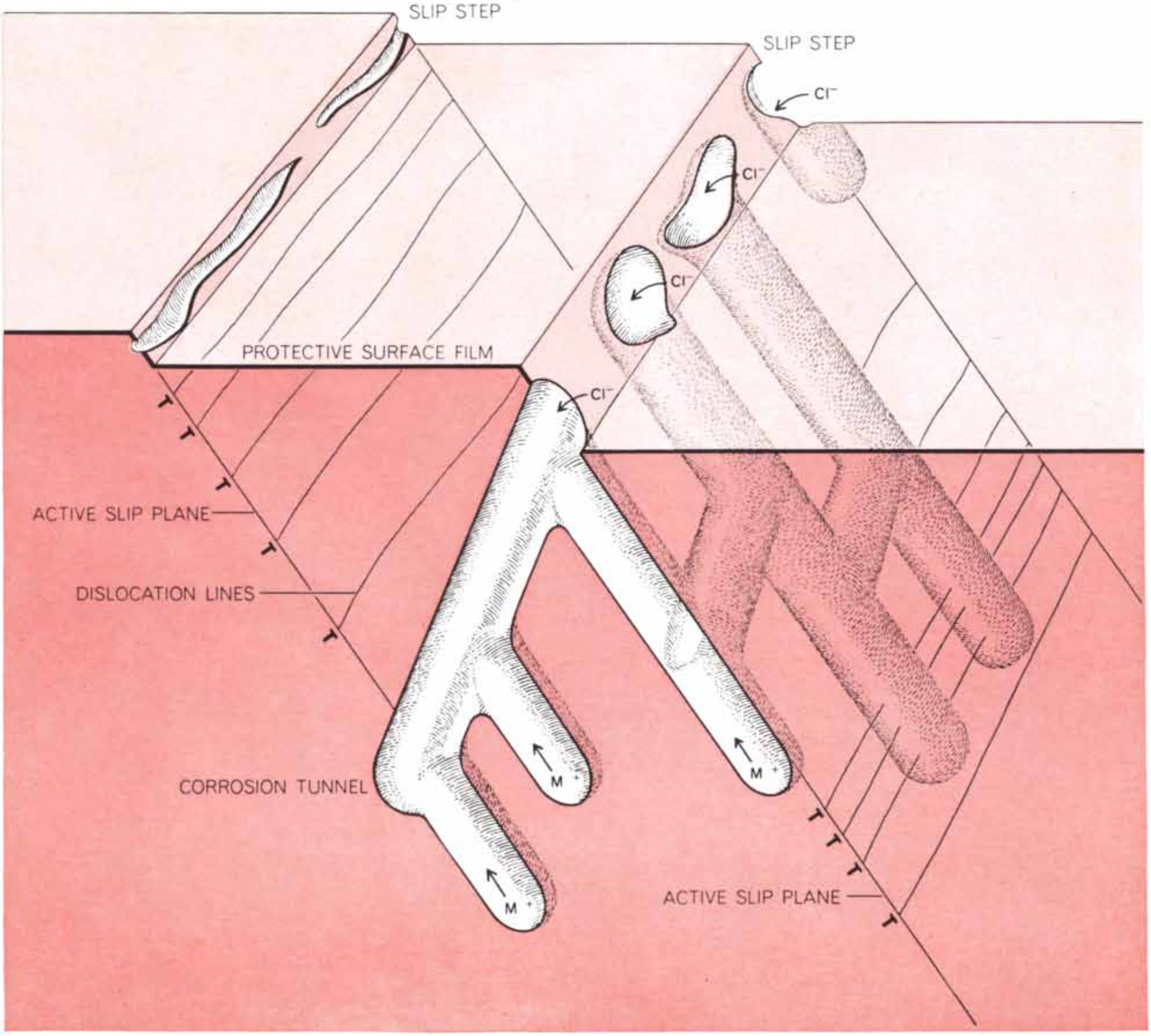
It is to be expected that the amount of damage suffered by the protective surface film is determined not only by the amount of slip but also by its distribution. The same amount of slip will expose a greater area of unprotected surface when all of it occurs on one plane (this is called coarse slip) than when it is distributed in small amounts over several planes (fine slip). It is more likely that the surface film would be broken in alloys forming coarse slip steps. This helps to explain the connection between the distribution of dislocations and the mode of stress-corrosion cracking: those alloys that form plane groups of dislocations also form coarse surface slip steps.

The validity of this argument can be demonstrated by a simple experiment involving a stainless steel that can take the form of martensite and austenite. First the steel is refrigerated to form a martensite structure and deformed to produce fine slip steps. Then it is exposed to the platinum-doped solution for a few minutes and examined in a light microscope. The fine steps are not revealed by platinum decoration (the chemical attack is randomly nucleated), indicating that this structure is resistant to stress-corrosion cracking. When the austenite version of the alloy is treated in the same way, however, it is deformed by producing coarse slip steps that *are* chemically active, and this structure is susceptible to transgranular cracking.

So far we have been concerned mainly with the nature of the nucleation site that leads to transgranular stress-corrosion failure. The equally important mechanism by which the corrosion tunnel forms at an active slip step is at present poorly understood. It is clear, however, that when the protective film on the surface of stainless steel is ruptured by the formation of a slip step, atoms of the alloy must come directly in contact with the corrosive environment and can enter into solution to become positively charged ions. The extent of this reaction is determined by the relative rates of corrosion and repair of the protective film. The formation of a locally high concentration of positive metal ions is expected to attract to the slip step chloride ions and other negatively charged ions in solution. In the case of stainless steels it is known that chloride ions (and other ions of the halogen family) cause a breakdown of the protective film. We also know that the solubility of the elements that compose the steel—iron, nickel and chromium—is unusually high in the presence of a strong concentration of chloride. The enrichment of chlorides in the region of a slip step therefore favors continued localized corrosion.

Another factor must be considered, however. The electric potential developed at the initial corrosion sites tends to retard the dissolution of metal in nearby areas, and it is thought that corrosion pits interfere with one another's growth if they are too closely spaced. This factor also tends to prevent individual pits from increasing in diameter, and since the planes of a crystal in which atoms are most closely packed are the slowest to dissolve, the walls of the pits will tend to become parallel to these planes. These considerations might explain why a given corrosion pit will grow in the direction in which atoms are most closely packed.

The aim of any investigation into the cause of a certain weakness is to discover a means of overcoming it. The results presented in this article indicate several possible ways in which we can hope to prevent stress-corrosion cracking. The process begins with the physical rupture of the thin, protective surface film; secondly, the metal atoms at the slip step enter the stress-corrosion-cracking environment as the protective film starts to cover the newly exposed



STEPS THAT LEAD TO CRACKING of a stainless steel are depicted. Under the action of an applied stress, dislocations move to the surface, forming slip steps that fracture the protective film and expose metal ions (*represented as* M^+) to the corrosive environment. Chloride ions (Cl^-) concentrate at a slip and retard re-formation of the protective film; this enables corrosion pits to elongate and ultimately form tunnels. The continued motion of dislocations on the slip plane prevents these corrosion tunnels from becoming inactive. They grow sideways, merging in the final stage of the stress-corrosion process (not depicted) to form a crack.

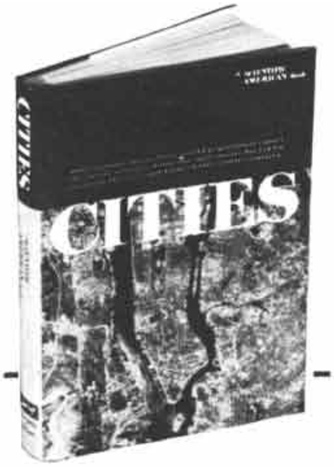
metal surface; thirdly, specific ions that hinder the formation of the protective film are attracted to the slip step and corrosion tunnels become nucleated; lastly, the motion of dislocations under the action of the applied stress ensures the continued growth of the corrosion pits. The prevention of any one of these important steps in the formation of a crack should eliminate susceptibility to transgranular stress-corrosion cracking.

One obvious approach is to try to reduce the damage to the protective film by using various metallurgical techniques that discourage dislocations from gliding in large groups on single planes. This approach has met with some success in the laboratory, but more must be done to develop a commercial alloy.

Another approach is to try to prevent the dissolution of metal at the slip steps. This can be achieved most easily by establishing an electric circuit in which the current flows in a direction opposite to the small currents generated during the dissolution of metal. An alternative method of reducing localized corrosion would be to hasten the repair of the protective film. In some cases this can be achieved by adding certain chemicals to the stress-corrosion environment. With both of these approaches it has been shown in the laboratory that the stress-corrosion cracking of stainless steels can be prevented under some environmental conditions.

Given the variety of industrial uses of alloys, it is often not possible to control closely the environment in which a given metal will be placed. The most desirable methods for preventing stress-corrosion failure should therefore involve some minor modification of the alloy itself. We could, for example, add small amounts of alloying elements that form insoluble compounds with the stress-corrosion environment. The precipitate formed during corrosion might then hinder the growth of corrosion tunnels and enable the protective film to re-form over the slip step.

In conclusion it should be mentioned that although we have dwelt mainly on the problem of the transgranular stress-corrosion failure of stainless steels, parallel experiments in our laboratory and in Nutting's laboratory (which is now at the University of Leeds) suggest that the same mechanism applies to many other susceptible alloys. There are also indications that the mechanisms of intergranular and transgranular stress-corrosion cracking are basically the same, in which case the applicability of our findings would be widened.



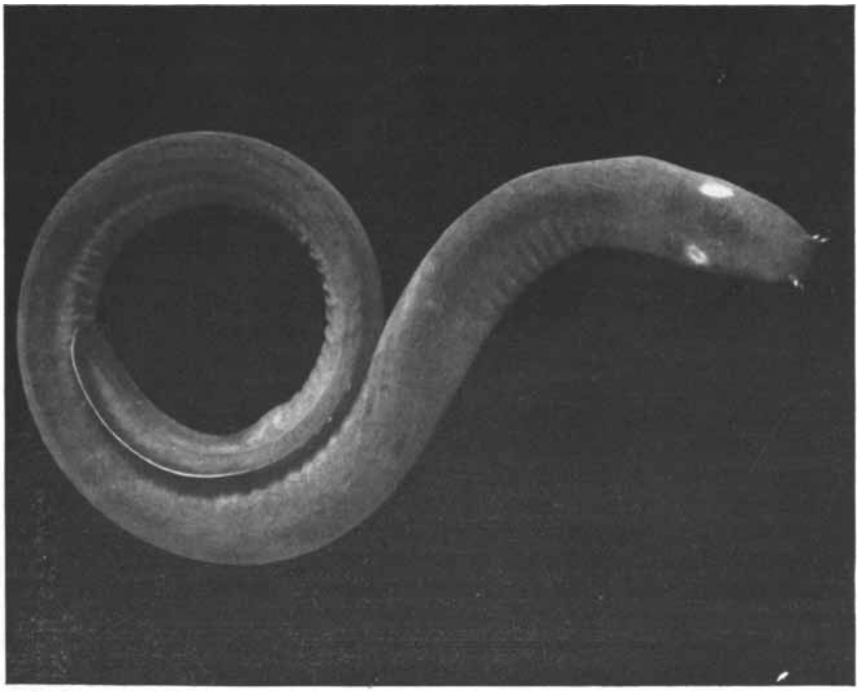
THE HAGFISH

This primitive animal has teeth on its tongue, secretes a viscid slime and can tie itself in a knot. It also has four hearts, the nature of which may clarify cardiac function in higher animals

by David Jensen

The reader may find it difficult to conceive of a fish that has four hearts, only one nostril and no jaws or stomach; that can live for months without feeding; that performs feats of dexterity by literally tying itself in knots. The organism nonetheless exists; it is called the hagfish. In appearance it is undistinguished: it is an animal Linnaeus classified as an intestinal worm and fishermen sometimes call the slime eel. Tasting strongly of fish oil and rubber-like in texture, it is not considered worth eating by man or any other animal predator. For a biologist, however, the hagfish holds much interest. Its anatomy and its habits are revealing. As the lowest form of true fish and vertebrate, the "hag" offers a matchless opportunity to investigate a stage in the evolution of vertebrates at a most primitive level.

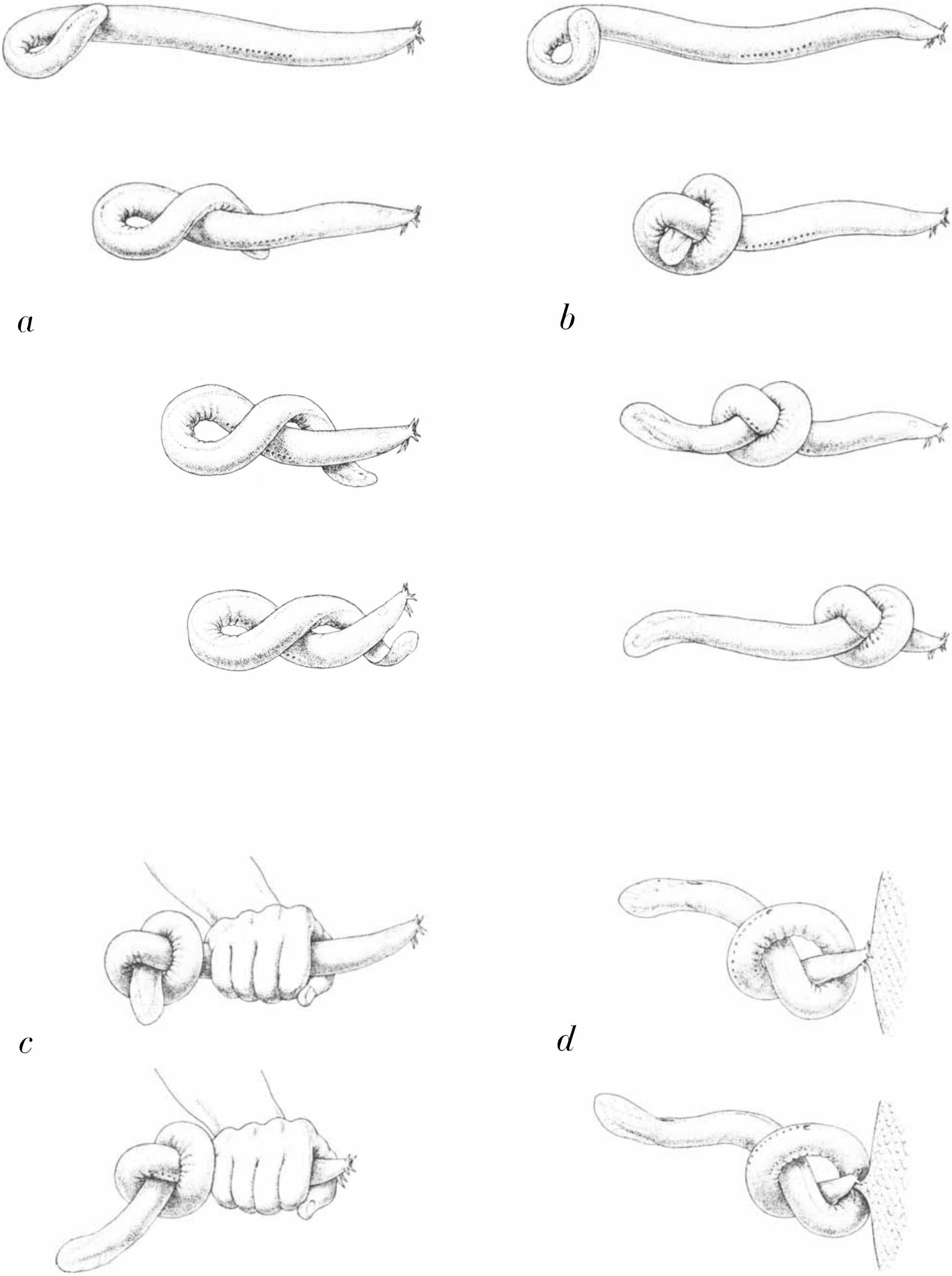
The hagfishes are undoubtedly a very archaic form of life. They belong to a class of animals (the cyclostomes, or round-mouths) that includes the blood-sucking lampreys [see "The Sea Lamprey," by Vernon C. Applegate and James W. Moffett; SCIENTIFIC AMERICAN, April, 1955]. The hags burrow into their prey (usually dead or dying fish) and devour the flesh and viscera, leaving only a bag of skin and bones. Although the hagfishes and lampreys are obviously primitive and ancient forms, unfortunately their ancestry and early development cannot be traced back in the geological record; no fossils of these soft-bodied animals have been found. Some investigators believe they may have descended from the ostracoderms, a group of ancient extinct armored fishes, because fossils of those animals show some of the same anatomical peculiarities, including a single nostril in the middle of the head and the lack of a lower jaw or paired fins. The question of cyclostome ancestry is far from settled, however.



HAGFISH RESTS at the bottom of an aquarium tank, its flattened oarlike tail curled into a circle. The light patches on either side of the head are the animal's two pigmented eyespots; these and a few other photosensitive skin areas allow the virtually blind hagfish to discriminate only between light and darkness. The animal depends on olfaction and touch rather than sight to find the dead or dying fishes that are its usual prey; visible at the front of its head are two of the three pairs of fleshy barbels that the hagfish uses to feel its way about.

The hagfishes are particularly intriguing because they remain puzzling in many respects in spite of long study. Even their method of reproduction is still a mystery in its details. A century ago (in 1864) the Copenhagen Academy of Science offered a prize for a solution to the questions of how the hagfish reproduces; to date no one has been able to claim the award.

The hagfish is strictly an ocean dweller, living on the sea bottom, principally in the temperate latitudes. Its habitat is restricted by the requirement that the water must be cold and quite salty. There are about two dozen species of the fish; I shall devote my account mainly to the one I know best: a Pacific Ocean species, *Eptatretus stoutii,* which inhabits the western continental shelf of North America from Alaska to Baja California at depths ranging from as



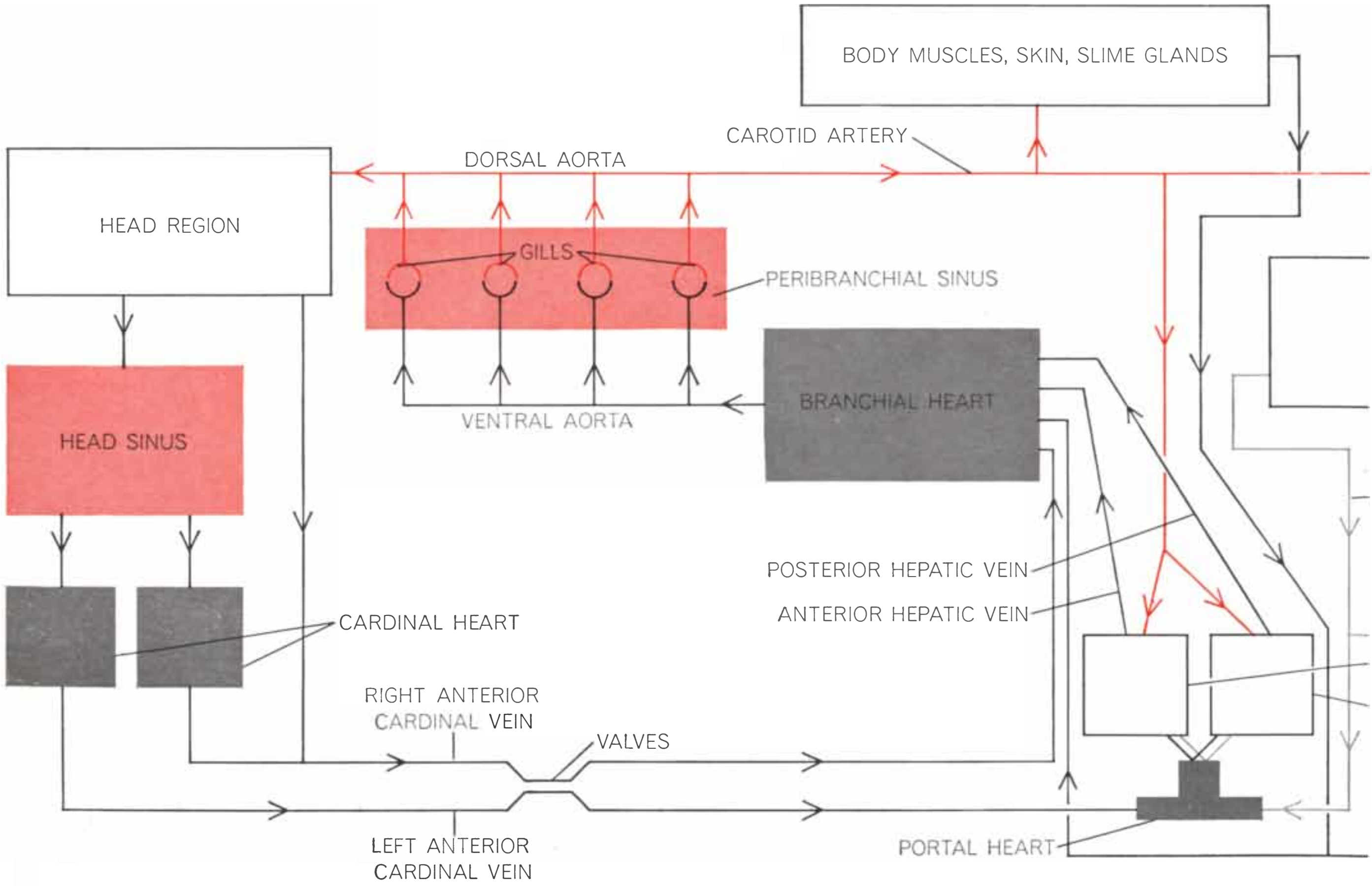
FLEXIBILITY of the hagfish is a result of its vertebrate "backbone" being formed entirely of cartilage. This enables it not only to curl into such odd configurations as a figure eight (*a*) but also to knot itself in ways that serve useful purposes. When the hagfish has become coated with slime, for example, it can rub the slime off by rolling a knot progressively from its tail to its head (*b*). The same movement helps the animal to escape capture (*c*) and to apply leverage when tearing at the surface of a food object (*d*).

little as 60 feet to as much as 1,800 feet.

From its habits one deduces at once that the hagfish is a remarkably sluggish animal. It spends much of its time lying quietly on the sea floor or in a burrow in the muddy bottom. (It appears to dislike sand and to avoid sandy areas.) When hungry, it is capable of swimming rapidly with a sinuous, snakelike motion, but normally it is quite torpid. Evidently it needs to feed only at infrequent intervals; it stores a high content of body fat and has a low rate of metabolism, abetted by its cold environment. Analysis by Winton Tong and his co-workers at the University of California at Berkeley has revealed that the hagfish produces very little of the metabolism-activating thyroid hormone thyroxin. In my laboratory at the University of California at San Diego a female hagfish has gone as long as seven months without feeding and at the end of that time has even laid a full quota of eggs (although the eggs were infertile).

As can be expected of an animal that lives on the dark sea bottom, the hag is almost completely blind. It has only rudimentary eyes—two pigmented cups in its head that serve as retinas—and a few sensitive skin areas on its head and around its cloaca that can discriminate light from darkness. In compensation for its lack of vision the animal has keenly developed senses of smell and touch. Serving the sense of touch are three pairs of barbels, or fleshy tentacles, around the mouth and nostril on the front end of the head. When the hagfish is hungry, it goes hunting for food by raising its head, extending its barbels and dilating its nostril. It swims along slowly, turning its head gently from side to side like a

HAGFISH IN PROFILE shows an array of tiny pores along its side from head to tail; these are the openings that lead to the slime glands, from which a milky fluid exudes when the hagfish is disturbed. The larger opening, to the rear of the 11 visible gill exit ducts, is an outlet for any of the water, drawn in through the single nostril, that has not been discharged through a gill exit. Hidden in this pharyngeal duct is the 12th gill exit. The hagfish's four hearts are in the areas outlined in color (*see illustration below*).



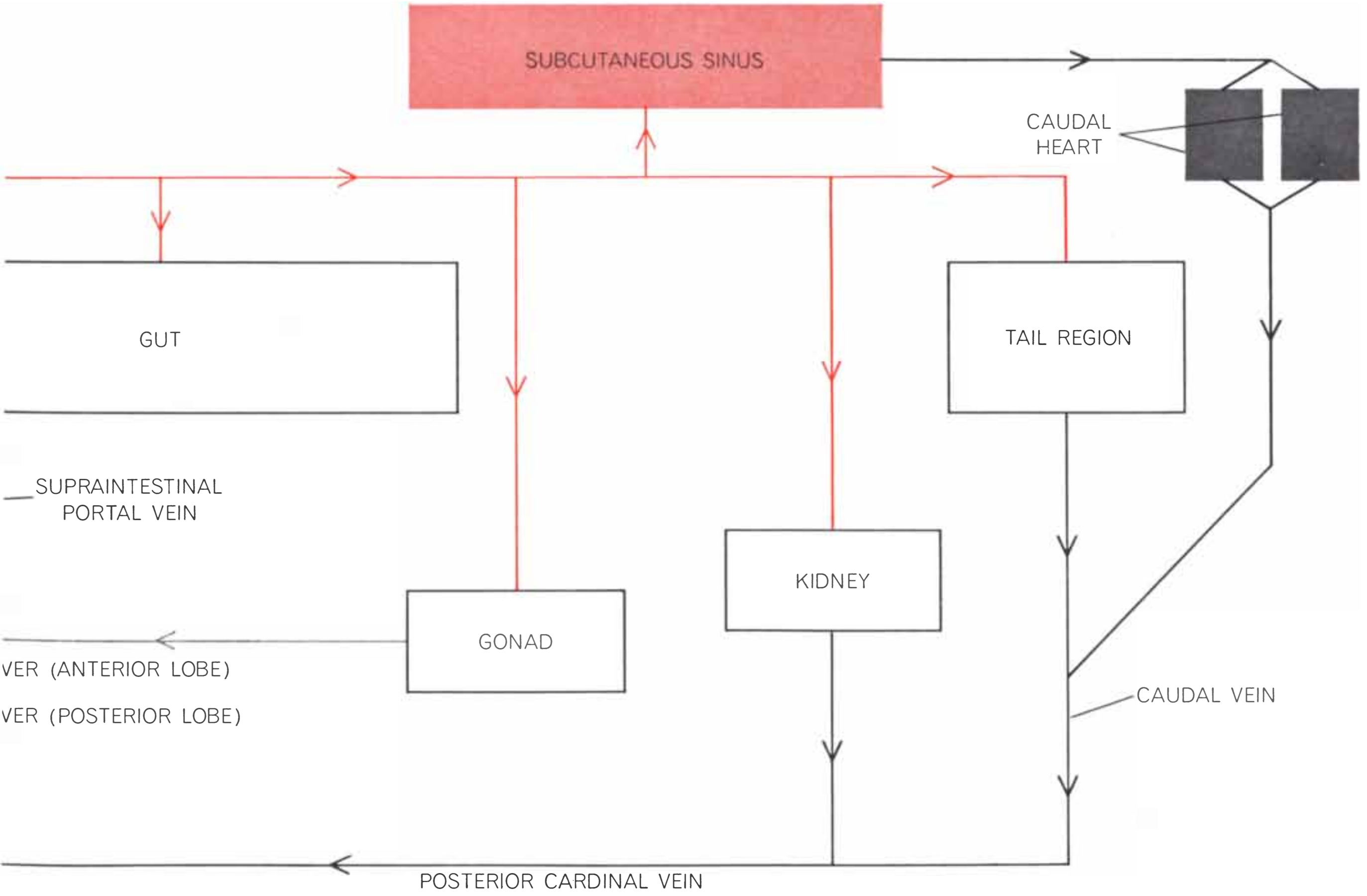
PRIMITIVE CIRCULATORY SYSTEM of the hagfish is shown as a block diagram. The system requires four hearts (*gray areas*) because in three major body regions (*colored boxes*) the blood percolates through large open spaces before reentering blood vessels; this free flow produces a sharp drop in blood pressure on the venous side of the circulatory system. The action of the cardinal dog sniffing the air. The fish makes its way upcurrent toward a food odor it has detected; once it has located the food it darts in and feeds voraciously and quickly. Hagfishes are primarily scavengers on dead or dying fish, but they will also eat worms when the preferred fare is not available.

The hagfish makes its entry into the body of a fish by means of strong, horny rows of teeth on the sides of its tongue [*see illustration on next page*]. Thrusting the tongue outward, it rasps pieces of tissue from its quarry. When the hagfish needs extra leverage to tear flesh out of a larger fish, it loops its body into a knot and thereby augments the strength of its pull by pressing the knot against the side of the fish [*see "d" in illustration on page* 83].

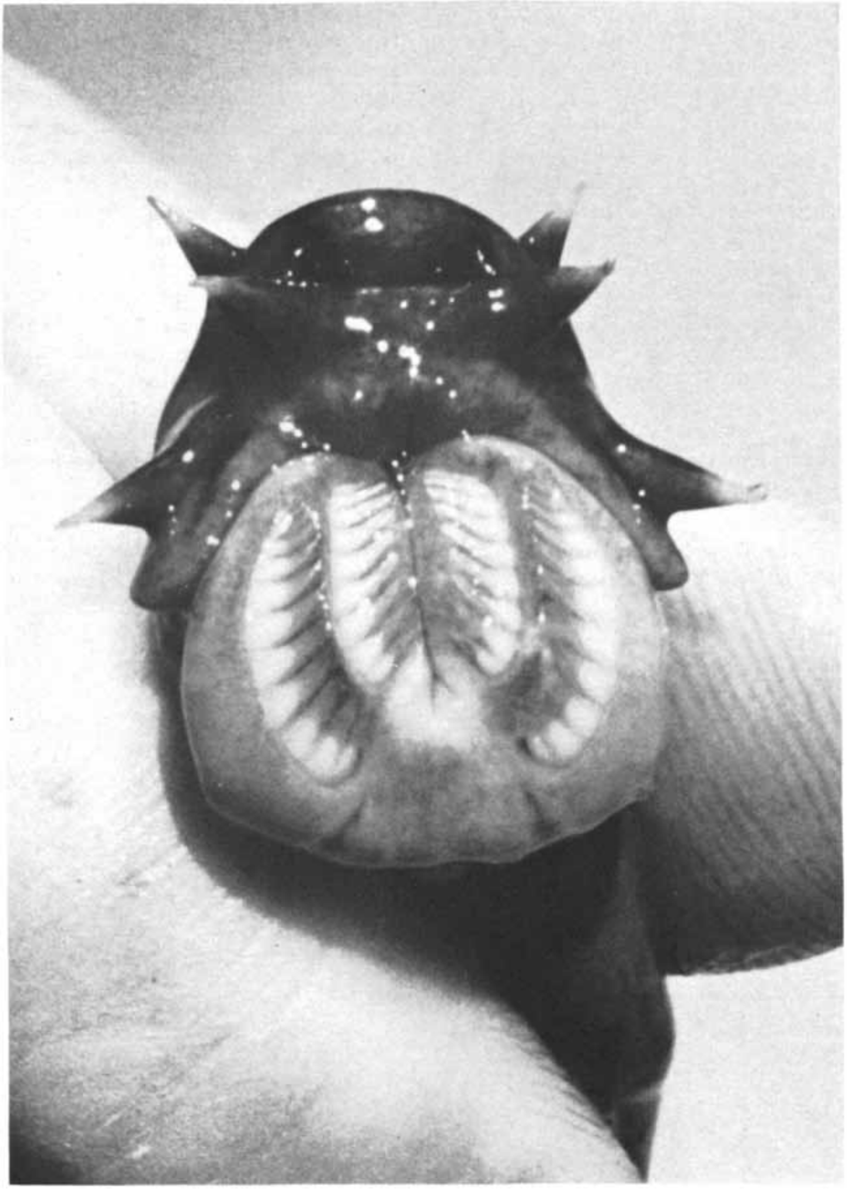
The knotting ability of the hagfish, altogether unique in the animal kingdom, serves more than one purpose. Among other things, it provides the hagfish with a cleaning mechanism. The animal's principal means of self-defense, which apparently helps to account for the fact that it has no known natural predators, is its ability to cover itself with a slippery slime. When it is disturbed or roughly handled, the hagfish will exude drops of a milky fluid through tiny pores situated in two rows along the lower sides of its body from the snout to the tip of the tail. On contact with the seawater, threadlike cells in this fluid break open and, with the water, form an extremely tenacious slime. In its cocoon of slime the hagfish is almost impossible to grasp. Afterward, however, the animal must free itself of the slimy coat lest it suffocate because of blockage of its gills and nostril. The supple hagfish accordingly loops its body into a half hitch, pulls itself through the loop and thus wipes off the slime. By the same maneuver the animal can generate enough pulling power to slide out of a man's grip. The hag is rather versatile as a contortionist: in addition to the half hitch it can also form a figure-eight loop.

Let us look closer into the anatomy of this remarkable animal. The hagfish is only a rudimentary vertebrate. Its "backbone" is a notochord, formed entirely of cartilage; hence its suppleness. The average adult Pacific hagfish is 10 to 15 inches long, with a cylindrical body flattened toward the rear end into an oarlike tail. On its head are two oval spots of light-colored skin that signify the location of the "eyes"; whether these are seeing organs in the early stages of evolution or degenerate remains of more complex eyes such as lampreys have is not known. Along the lower sides of the hagfish behind the eyespots are two rows of about a dozen whitish dots that are the gill openings. Spread more widely over the body are the much smaller slime pores, the openings of slime glands situated inside the body.

The hag's respiratory system has several unusual features. Its main oxygen supply comes from the water drawn in through the nostril. On entering the throat the water is pumped by a pair of muscular flaps (the velum) to the dozen or so pairs of gill pouches arrayed along the body [*see upper illustration on page* 87]. There the water



and portal hearts (*bottom left and center*) helps to restore some of the pressure lost in the peribranchial and head sinuses; the caudal heart (*top right*) does the same for the venous blood draining from the subcutaneous sinus. Where the arterial blood (*color*) enters a labeled box and venous blood (*black*) leaves it, the organs that are specified receive oxygen by means of a normal capillary bed.



RASPING TONGUE, set with parallel rows of teeth, lets the hagfish burrow into its prey. The hagfish then devours both flesh and viscera until nothing remains but skin and bones.

flows out of the gill openings by way of ducts, while blood flowing in the opposite direction in vessels in the gills picks up oxygen from the water. This "countercurrent system," which facilitates the rapid exchange of gases, is common in fishes.

If foreign bodies or slime happen to clog the hag's nostril, it emits a powerful sneeze to clear the passage. Just how this is accomplished is not clear; the sneeze is not simply a reversal of the velum's inward pumping. It seems that the hagfish may be able to obtain some oxygen through its skin as well as through the nostril-and-gill apparatus, because the animal can survive for a considerable length of time even when its nostril is plugged.

The cardiovascular system of the hagfish is a curious and complex affair [*see illustration at bottom of preceding two pages*]. Its principal organ is the branchial heart, which pumps blood through the gills and thence by way of arteries to the rest of the body. Assisting this main pump are three accessory hearts, all on the venous side of the circulation. They are necessitated by the peculiar fact that part of the hagfish's venous circulation is not connected to the arterial side in the ordinary way. In most of its organs the animal does possess a typical vertebrate circulation—the blood passes from the arteries to the veins by way of a capillary bed in the nourished tissues; this is true of the gills, the gut and the body muscles. In certain areas of the body, however, there is no capillary bed; instead the arterial blood is discharged into large open spaces, called sinuses, through which it percolates before entering the veins. (An "open" circulation of this kind is common among invertebrates but rare in a vertebrate.) The result is that the blood pressure on the venous side of the animal's circulation is very low. Consequently the three auxiliary hearts are required to pump the blood back to the branchial heart. Each returns blood from separate parts of the body.

In addition to the four pumps, certain muscles of the body take part in driving the blood forward. The gill pouches can assist the branchial heart by performing rhythmic contractions that milk the blood in the gills toward an aorta and the carotid arteries and thence into the rest of the body. On the venous side, when the animal is active, contractions of the body muscles against various blood vessels help to squeeze blood toward the branchial heart. Strategically placed throughout the body are valves that prevent any backflow.

Perhaps the most curious aspect of this complex circulatory system is that the several hearts are not coordinated with one another. Each beats at its own pace, quite independently of the others. Indeed, the hagfish has no sympathetic nervous system or any other mechanism that could serve as a general coordinator of these organs.

The branchial heart itself is a three-chambered organ consisting of a sinus venosus (a cavity to which the veins deliver their blood), an atrium (the heart antechamber) and a ventricle (the pump). Surprisingly, there are no coronary arteries to nourish the branchial heart tissues (or the other hearts, for that matter). They are nourished only by the venous blood that bathes them. The branchial heart lies close to the animal's two-lobed liver, and it pumps its output to the gills by way of a ventral aorta.

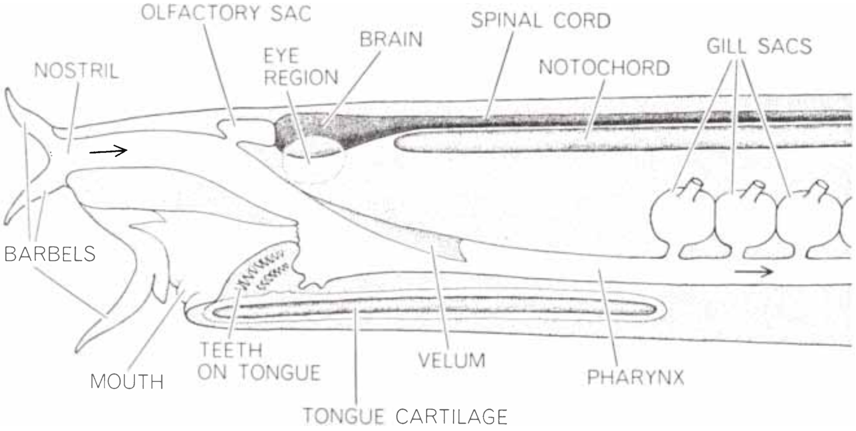
Ordinarily when the hagfish is at rest, this output is small, the blood pressure developed by the branchial heart amounting to only about one to five millimeters of mercury. When the animal's activity requires it, however, the heart can increase this pressure to about 25 millimeters of mercury. For more than half a century, ever since it was discovered that there are no nerves regulating the beat of the hagfish's heart, that fact has been one of the main reasons for research interest in the animal. How does the hagfish raise its cardiac output to meet increased demands? More fundamentally, what mechanism is responsible for the rhythmic contractions of the heart muscles that constitute its heartbeat? This question is particularly interesting because the heart of an adult hagfish resembles in several basic respects the heart in the early embryo of a mammal. Like the hagfish heart, the myocardium (muscular wall) of the mammalian embryo's heart contracts rhythmically without regulation by nerves. What makes it do so? Here we are close to the key to the origin of the heartbeat, and the hagfish heart, which is large enough for experimental studies, offers a convenient subject for fundamental investigation of the question.

Physiological studies show that the stimulus responsible for the increase of output by the hagfish's branchial heart is an increase in the inflow of venous blood into the heart. The distension of the heart by this augmented load produces two effects: it speeds up the heartbeat and it causes the heart muscles to contract with more force. Thus it obeys the well-known Frank-Starling law of the heart observed in the higher vertebrates: within limits, the more the heart muscle is stretched, the more strongly it contracts.

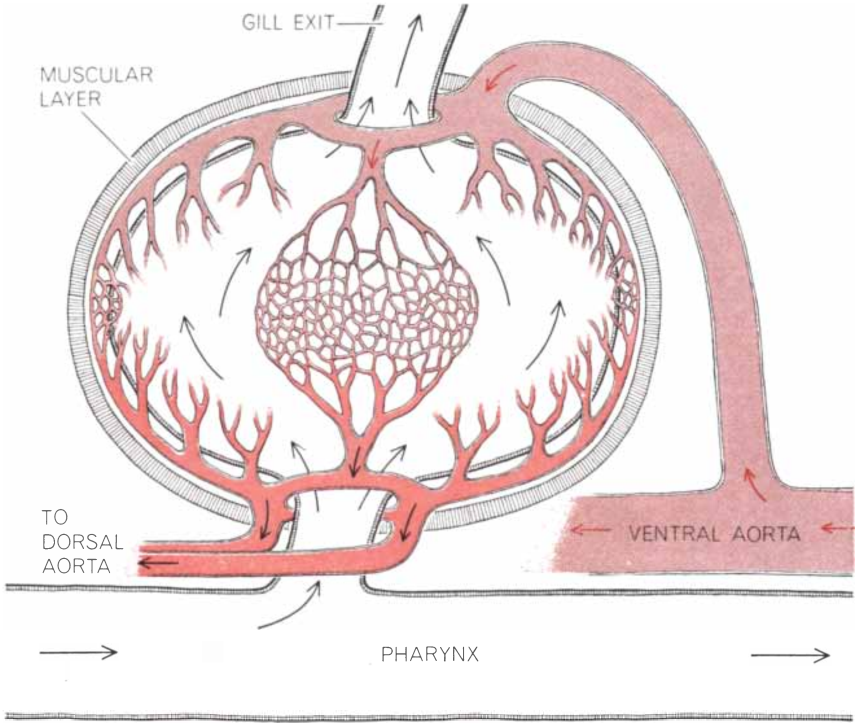
As for the pacemaking mechanism that maintains the rhythm of the hagfish heartbeat, a few clues have turned up. The ventricle has a comparatively thick, spongy wall. Its muscle tissue is striated, like the cardiac muscle tissue of other vertebrates, but the cells are smaller, spindle-shaped and woven together loosely in a framework of connective tissue. The hagfish heart is amazingly tenacious of life. Removed surgically from its owner and planted under the skin of another hagfish, where it floats in normal body fluids, the transplanted heart will beat strongly for three weeks or longer, as I have found in repeated experiments with the branchial heart and the portal heart, one of the auxiliary pumps in the hagfish. These hearts will beat for several days even in ordinary seawater or an artificial salt solution similar in composition to seawater. Furthermore, tiny fragments of the heart tissue can survive dissection: they will go on contracting rhythmically, each at the rate characteristic of the tissue from which it was excised.

From such experiments and exploration of the heart with microelectrodes we can draw the conclusion that the pacemaker cells responsible for exciting the muscular contractions are scattered randomly throughout the heart structure. Occasionally a microelectrode will puncture a cell that has electrical characteristics similar to those of cells in the specialized pacemaking nodes of the hearts of higher vertebrates. The coordinating mechanism that keeps the hagfish's branchial heart beating smoothly apparently lies in the sinus venosus; this area has a faster inherent rate of excitation than the other areas of the branchial heart and dominates them. Similarly, the coordinating mechanism for the portal heart seems to be localized in the last few millimeters of the vein from the gut where it enters the heart.

The portal heart is a tubular affair roughly in the shape of a *T*, one arm of the *T* receiving venous blood from the gut and the gonad, the other from the head end of the animal. This heart pumps the blood through the two lobes of the liver. The liver is between the



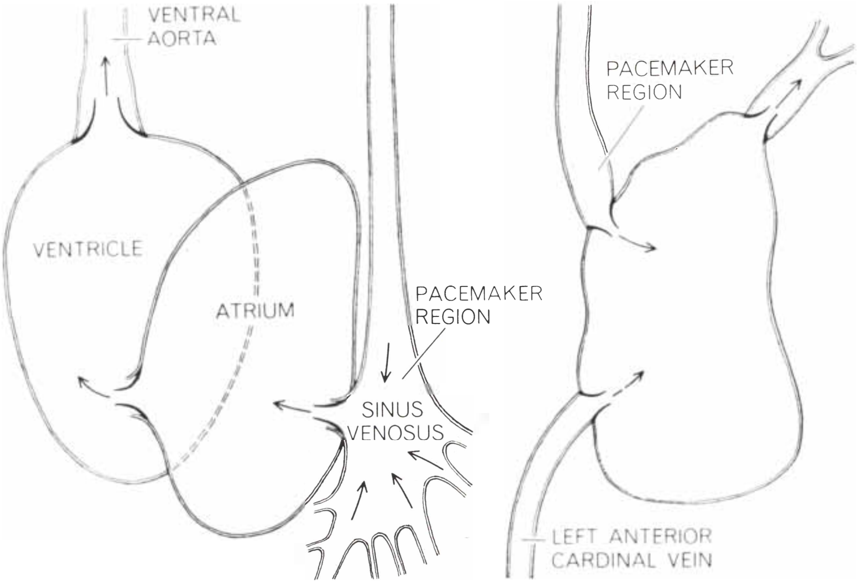
FLOW OF WATER from which the hagfish draws its oxygen enters the single nostril (*left*). When the water reaches the velum, a pair of muscle flaps (*center*), it is pumped both past and into a row of gill sacs, one of which is illustrated in section below. The hagfish has no jaws; the horny teeth with which it rasps its food grow in rows on its protrusible tongue.



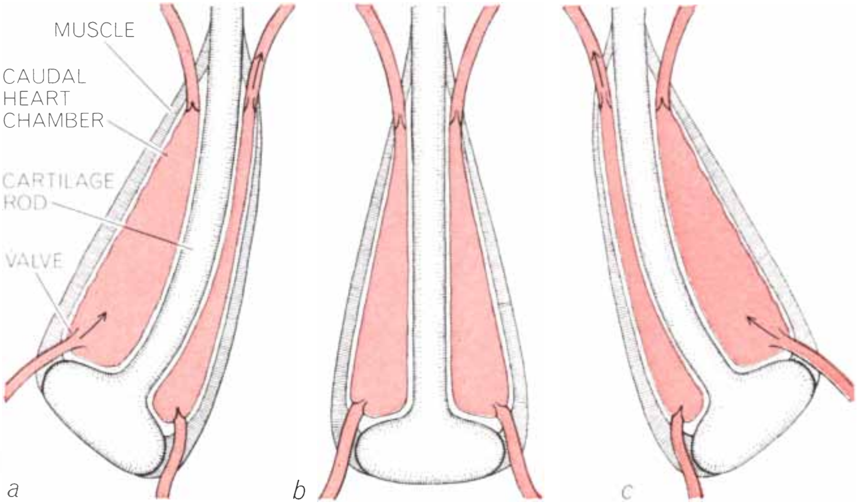
COUNTERCURRENT FLOW of water and blood in the hagfish gill sac (*arrows*) facilitates gas exchange that simultaneously adds oxygen to and removes carbon dioxide from the fish's blood. The light and dark colors distinguish oxygenated from nonoxygenated blood. Countercurrent flow is common in fishes, but only hagfishes have this gill sac arrangement.

branchial heart and the portal heart; the portal heart lies toward the lower right side of the hagfish. Anatomically and physiologically the portal heart shares many attributes of the branchial heart; it is smaller and simpler in structure, however, and usually beats at a faster rate.

The hagfish's other two hearts can be considered true hearts because they pump blood, but in structure and mechanism of action they differ basically from the branchial and portal hearts. One, called the "cardinal heart," pumps venous blood from the head region; the other, called the "caudal heart," is located in the tail. The cardinal heart consists of a pair of sacs in the head region of the animal. It has no muscles or machinery of its own for producing rhythmic impulses; its pumping action actually is operated by rhythmic contractions of skeletal muscles that lie outside the sacs in the head region. These contractions, activated by nerves, compress the sacs and thereby squeeze the blood in the cardinal veins toward the branchial or the portal heart.



MAJOR PUMPS that power the hagfish's circulatory system are the branchial heart (*left*) and the portal heart (*right*). The sinus venosus of the branchial heart collects blood from all parts of the body; the blood enters the atrium and is then pushed on to the gill sacs by rhythmic contractions of the ventricle. The portal heart, in contrast, pumps only part of the blood supply (*see illustration at bottom of pages 84 and 85*). This blood enters the liver and passes on to the branchial heart. Both hearts are thus closely related, but they do not have a common rhythm. Instead each one beats at a rate determined by the volume of blood reaching its "pacemaker" region, an area with the fastest inherent excitation rate.



MINOR PUMP, the caudal heart, lies less than half an inch from the end of the hagfish's tail. A cartilage rod lies between two valved chambers; paired muscles, attached to the rod, pass along the outside of the chambers. Contraction of the left muscle (*a*) expels blood collected in the right chamber and allows the left chamber to fill; the opposite contraction (*c*) empties the left chamber and fills the right one. The caudal heart beats irregularly; unlike the two nerveless major hearts, it is controlled by nerve impulses from the spinal cord.

The caudal heart, like the cardinal heart, consists of a pair of tiny sacs, guarded by valves at their inlets and outlets. Between these two small chambers is a rod of cartilage, to which are attached two muscles running the length of each sac on the outside [*see lower illustration at left*]. The two muscles contract alternately in an oscillating rhythm, bending the rod first in one direction and then in the other, so that the two sacs are compressed alternately, as the illustration shows. In effect the organ acts as a reciprocating pump, pumping blood from each chamber alternately while the other one fills. The strangest aspect of the caudal heart is its apparent unimportance. To begin with, it is so small—about the size of a pinhead—that its pumping capacity must be very small indeed. Moreover, its operation seems to be quite capricious. It will stop beating for a time for no obvious reason and then start again. In sharp contrast to the branchial and portal hearts, the caudal heart is activated by nerves, the stimulating impulses coming from a reflex center in the spinal cord. Stimulation of the hagfish's skin will inhibit the caudal heartbeat completely; so does extreme activity by the animal. All in all it appears that the caudal heart plays only a minor role and is not necessary for the animal's survival. Removal of the tail, including the caudal heart, apparently does not inconvenience the hagfish greatly, aside from handicapping its swimming.

Still another, and more important, surprise has turned up in the investigation of the hagfish's hearts. Examining the cells of the branchial and portal hearts in the Pacific hagfish with the electron microscope, I found some large, granule-containing cells that looked like cells of a gland rather than heart cells; independently, Gunnar Bloom and his collaborators in Sweden discovered the same cells in the branchial and portal hearts of the Atlantic hagfish (*Myxine glutinosa*). Experiments revealed that these cells, which lie below the lining of the heart (the endothelium), secrete the common adrenal hormones adrenalin and noradrenalin. I have isolated a third heart-stimulating substance, probably also a hormone, that may possibly be produced by the same cells. It seems, then, that the hagfish heart is not only a pump but also an endocrine gland! Considering that the hagfish has no adrenal medulla or sympathetic nervous system (the usual regulator of the adrenal gland), it is indeed strange to find adrenal hormones in its nerveless heart.

Like the cardiovascular system, the hag's digestive system also has its striking features. From the throat to the anus a long, rather unspecialized intestine runs straight through the animal. There is no stomach as such; the intestine is merely divided into a foregut and a hindgut by a circular band of muscle behind the throat that serves to prevent respiratory water from flowing back into the digestive region. When the animal feeds, this muscle relaxes, enabling food to pass into the hindgut. Interestingly enough, as it passes through the gut a mass of food becomes enveloped in a thin, highly permeable coating of cells (like a sausage in its skin), much as in insects. This "peritrophic membrane" surrounds the waste matter left within it when the waste is discharged.

The lining of the intestine is corrugated by long ridges that increase its surface area for the absorption of nutrients. It seems that in the hagfish the liver and the gallbladder, judging from their comparatively large size, probably play active roles, along with the intestine, in the digestion of food. The hagfish pancreas, unlike that of most vertebrates, is divided into two completely separate parts, one secreting digestive juices, the other insulin. The hormone insulin presumably regulates the blood-sugar level in the hagfish as it does in higher vertebrates. Surprisingly, however, it has been reported that surgical removal of the insulin-secreting portion of the hagfish pancreas, which in other vertebrates would quickly lead to a diabetic condition, does not result in any elevation of the sugar level in the blood, even as much as five days later. This peculiar circumstance remains unexplained. Another unusual finding is that the gut of the hagfish not only is a digestive organ but also produces the red blood cells.

One of the most striking demonstrations of the hagfish's primitive physiology is its salt and water balance. The salt concentration of its blood is essentially the same as that of the seawater

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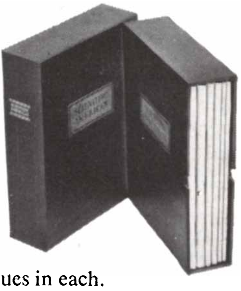

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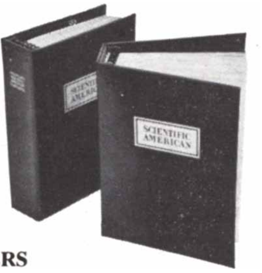

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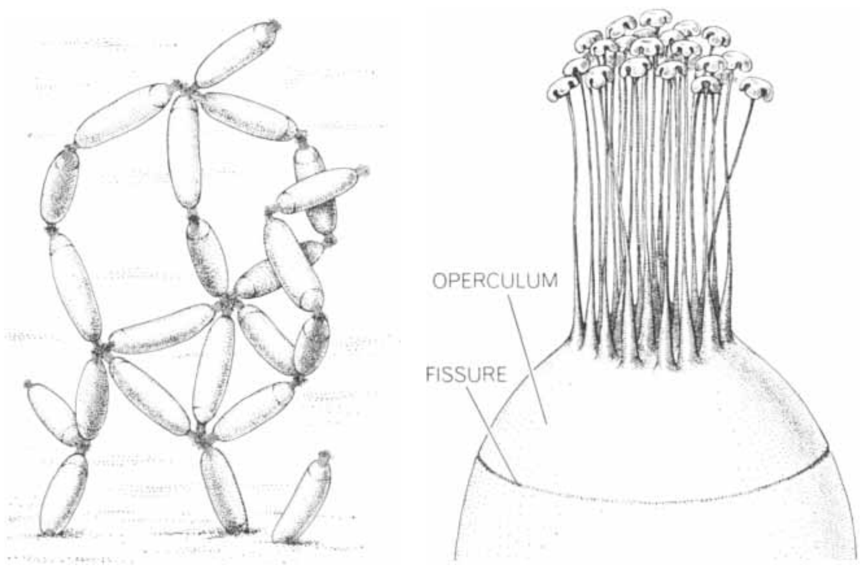


HAGFISH EGGS are much larger than the eggs of more advanced fishes and are produced in far smaller numbers. They are nearly an inch long, with tufts of filaments at each end that serve to attach them to one another (*left*) and to the ocean floor; the average number of eggs per spawning is 22. At maturity the egg breaks apart along the line of the opercular fissure (*right*) and the hagfish then emerges as a small adult rather than in a larval form.

in which it lives; in this the hagfish is unique among marine vertebrates. The reason is that it has only a very primitive kidney. The kidney consists of two parts: the pronephros, whose function is unclear, and the mesonephros, or kidney proper, which filters the blood. This organ, however, lacks the tubules that in other vertebrates enable the kidney to select substances in the blood for excretion or reabsorption into the body; the hagfish kidney consists only of Malpighian corpuscles containing the filtering glomeruli. As a result the animal has little ability to regulate the excretion of salt through its urine, and it cannot survive long in water that has either a very high or a very low concentration of salt; it is barred, for example, from living in an estuary where the salt concentration is diluted. A few experiments suggest that adrenocortical hormones are probably responsible for what little capacity the hagfish has for regulating the osmotic pressure of its blood.

Finally, the hagfish provokes much curiosity by certain enigmas that surround its method of breeding. Judging from the tremendous numbers of hagfishes found in certain localities, the organism's reproduction and survival are notably successful, yet details of the process are shrouded in uncertainty. No hagfish has yet been coaxed into producing fertile eggs in the laboratory.

The female hagfish is usually much larger than the male. This observation gave rise to the idea that the animal was a protandric hermaphrodite, that is, it starts as a male early in life and then develops into a female. Detailed investigation of its development showed, however, that when it is young the animal is in an "indifferent," or neutral, form combining the elements of both sexes and that it becomes either a male or a female as it matures.

The hagfish, along with the lamprey, is set apart from all other vertebrates by the fact that it possesses only a single gonad, or sex organ. The gonad is an elongated structure that extends the length of the animal from just behind the liver to the region of the cloaca at the rear; it hangs from a delicate membrane on the right side of the intestine in the abdominal cavity. In early life the forward part of the organ clearly has the nature of an ovary, whereas the hind third of its length is composed of immature testicular tissue. When the animal matures, the male or female portion of the gonad develops and the other part is repressed, presumably under the influence of hormones from the pituitary gland. Thus the mature hagfish becomes a distinctly differentiated individual: a large female with a fully developed ovary or a male with a developed testis.

Neither the male nor the female possesses any copulatory organ that would allow fertilization of the female's eggs internally. The eggs must therefore be fertilized after they have been deposited in the seawater. The female's eggs and the male's germ cells are discharged not through specific ducts but through openings in the cloaca.

The eggs are extremely large for a fish: about an inch long, elliptical in shape and covered with a horny shell. The egg is yellowish, because it consists mainly of yolk. At both ends of the egg are tufts of filaments, which serve to anchor the eggs to one another and to rocks on the sea bottom so that they are not washed away from the spawning area. We do not know how the fertilization of the eggs is accomplished; what is clear is that they are not fertile when they are freshly laid by the female. Accordingly true hermaphroditism is ruled out. When the eggs hatch, the young emerge not as larvae but as small hagfish; in this they differ from the lampreys, which pass through a long larval stage after hatching.

Not the least remarkable of the many peculiarities of the hagfish is the apparently high survival rate of its young. Compared with other fishes, the female hagfish is a very small producer. It takes many months to develop the eggs within its body, and the average number laid at one time is only about 22—very few indeed compared with the thousands of eggs laid by other fishes at a single spawning. Yet the ocean abounds in enormous numbers of hagfishes. I myself have collected about 29,000 of these animals off the Pacific Coast—approximately 15,000 of them from one comparatively small area near San Diego. The almost astronomical fecundity of other marine organisms is offset by an extremely high rate of attrition among the eggs and the young, so that relatively few individuals survive to maturity. Quite evidently the hagfish is a far hardier animal.

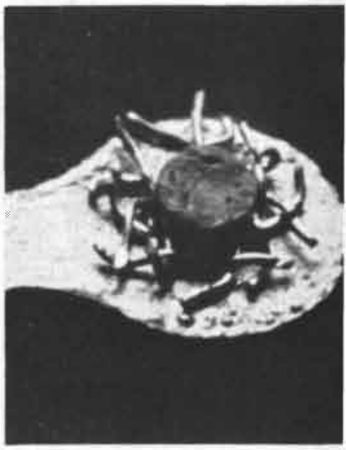
One reason may be its remarkable immunity to infectious disease. A wound in a hagfish will remain clean for weeks with no sign of infection (or of healing either). This is particularly surprising because no one has yet been able to discover the basis of the immunity. Robert A. Good and Ben Papermaster of the University of Minnesota School of Medicine have established that hagfishes do not manufacture antibodies; indeed, they apparently lack the thymus tissue that is usually involved in the synthesis of antibodies. I have searched for a possible antibiotic in the body of the hagfish but have failed to find any in its slime, skin, blood or body organs. Here is one more of the many provocative features that make the hagfish a most fascinating animal to study.

What gives with "compliant redundancy" at Western Electric?

With so much going on today in communications, there are often two sides to printed circuits. Connecting them and allowing for expansion and contraction of the boards, are sizable problems. What kind of through connection? Flanged eyelets? Solder? Plating? No. Eyelets loosen. Solder loosens. Plating cracks. Resistance is higher than it should be. Performance is off. And so rigid are Western Electric's requirements for reliability that a cracked through connector is an anathema. Equally rigid, however, are our requirements for economy.

The solution, as worked out by engineers of Western Electric and Bell Telephone Laboratories, satisfies both requirements with elegant simplicity. Braid 16 gold-plated wires around a silicon rubber core just thick enough to press the wires against the edge of the hole. Cut off a snippet and stuff it into the hole, leaving about 1/16″ protruding on either side. Spread the wires out, press them down, solder.

Now, with braided wires going through the hole at a slant, they accept expansion and contraction of the boards — whence compliant. And with 16 wires, even if some don't connect properly, others will do the job — whence redundant. Hence the Bell System's passions for reliability and economy (and Western Electric's as a part thereof) can, in a small but not insignificant way, be satisfied.



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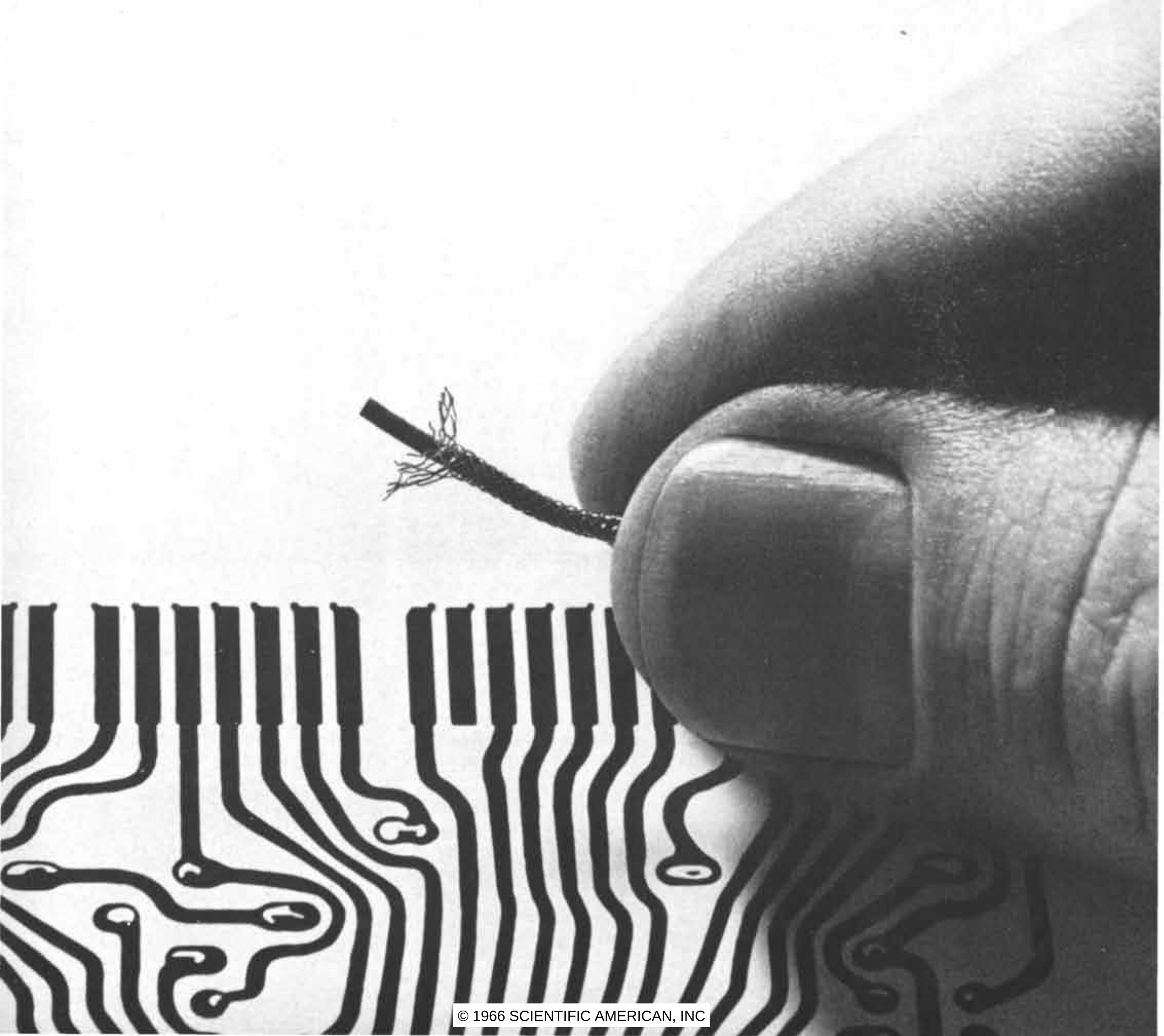


The Control of Snow Avalanches

As more people and their works push into mountain areas the hazard of snowslides increases. A number of methods have been developed both to prevent the slides and to provide protection against them

by Edward R. LaChapelle

The hazard of snow avalanches to life and property increases from year to year. It is enhanced by the general rise in population, which places more communities and structures in the hazardous areas; by the growing popularity of skiing, which attracts ever more thousands to the snowy mountainsides, and by the expanding networks of communications—highways, pipelines, power lines, electronic relay systems—whose mountain crossings must be protected. Concern about the avalanche problem is by no means new, but in recent years there has been an intensification of efforts to find effective ways of controlling the hazard. Several useful techniques have been developed, and other interesting ideas are under study.

There are two basically different types of snowslide, one much more dangerous than the other. They are known respectively as "loose snow" avalanches and "slab" avalanches [see "Snow Avalanches," by Montgomery M. Atwater; SCIENTIFIC AMERICAN, January, 1954]. Loose-snow slides occur frequently, but they seldom grow very large or cause much damage. It is the slab type of avalanche, which sets in motion as one massive body a large area of snow, that presents the principal menace and is the main object of control efforts.

Investigations of the predisposing conditions are focused essentially on the structure and nature of the snow itself, particularly its cohesion. This has two aspects: on the one hand, the strength of bonding between the snow crystals within a layer; on the other, the degree of bonding of one layer to another. Cohesion between the snow particles depends in large part on the age and nature of the snow crystals, which vary considerably in form. Crystals of certain compact, nonstellar types tend to become firmly cemented together. Weather conditions also play a part: strong bonding between crystals is encouraged by wind-packing and by riming—the accretion of supercooled water droplets as the snow is deposited.

A well-cemented layer of snow can cling to the steepest mountainside. Whether or not it will do so depends, however, on how securely the slab is anchored to an underlying layer of snow or the ground. This bond may be insecure to start with or it may be weakened by certain natural processes.

A smooth layer of ice under the slab can be a highly insecure foundation. Such a layer may have been formed by freezing rain before the upper snow fell. In the spring a lubricated layer is often produced under the slab by meltwater that percolates below it. Of the various processes that may undermine the slab, one of the most treacherous—a prime cause of dangerous avalanches—is "constructive metamorphism" of the snow. This is most likely to take place in comparatively fluffy snow subjected to a steep temperature gradient, particularly at high altitudes. Such snow sublimates—evaporates from the solid state. The water vapor is then redeposited within the snow layer as new crystals in the form of hoar frost. An entire layer may be converted to hoar in this way. The metamorphosed snow has a fragile structure, and any snowfall deposited on this "depth hoar" has a precarious foundation. A slab on top of depth hoar can easily be triggered into an avalanche.

Any snow layer on a mountainside tends to creep gradually down the slope under the influence of gravity. Stresses develop within the layer, because of variations in its depth and irregularities of the terrain, and they generate zones of tension. The conditions are then ripe for a sudden fracture of the slab. On a slope of 30 degrees or more a very slight disturbance, even as small as a clump of snow falling from a tree, can provide the trigger. The slab may crack along a long fracture line and start sliding with almost explosive violence. Even a layer of soft, new snow, if its bond to the

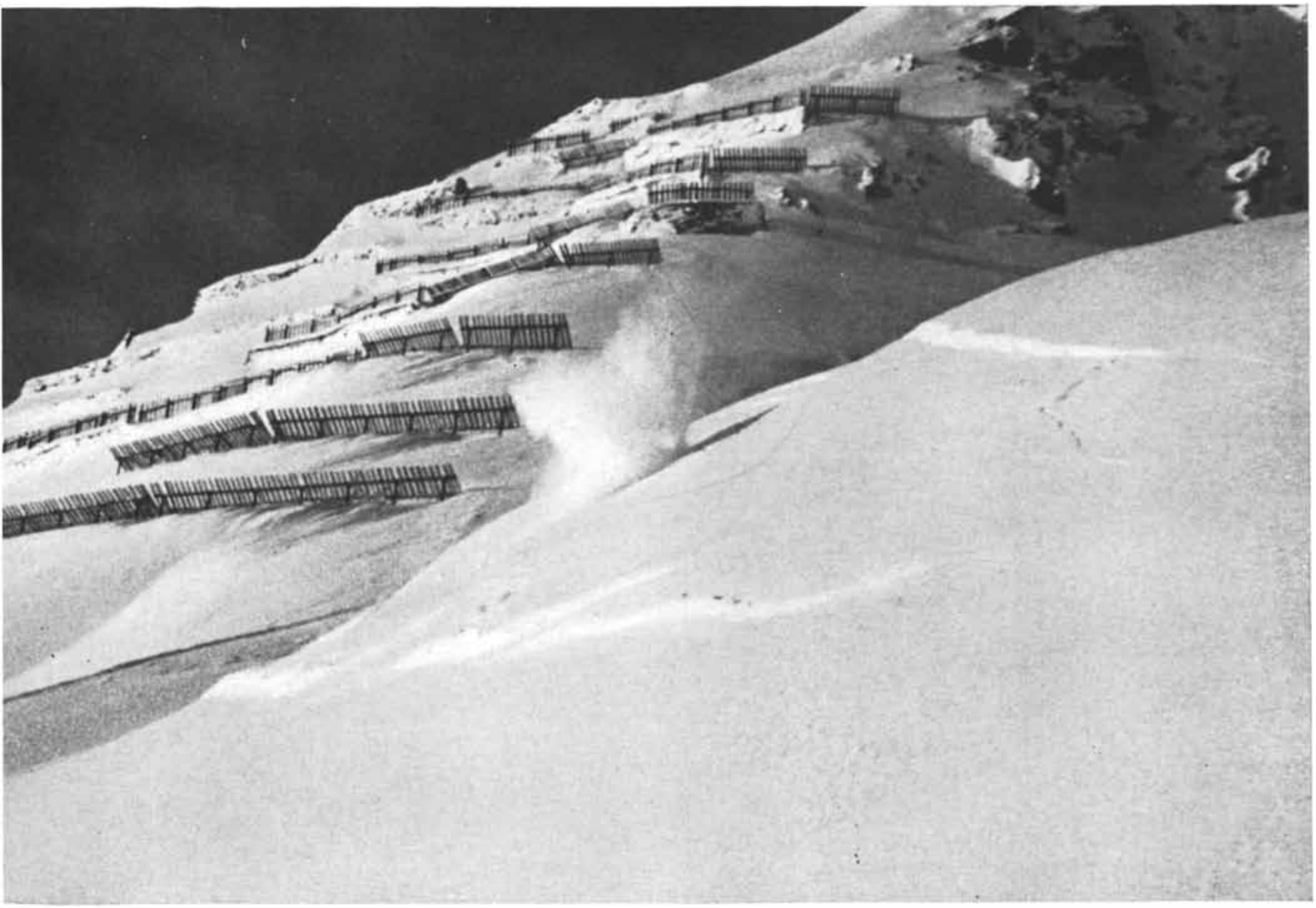
TWO METHODS of avalanche control can be seen in this photograph made near Davos in Switzerland. One method involves alter-

substratum is sufficiently weak, can behave as a slab and break away in this fashion.

A large avalanche of wet snow will often strip the entire snow cover from the soil and sweep all vegetation before it. A slide of dry snow sometimes generates a huge cloud of snow particles that, like a heavy gas, charges ahead of the main mass of the avalanche at velocities as high as 200 miles per hour. This "wind blast" can be powerful enough to dislodge a steel bridge or mow down a stand of big trees like a giant scythe.

The most elementary defense against avalanches is to attempt to forecast their occurrence so that people and transient traffic can be warned to stay clear. Although physical studies and experience have armed us with many clues, avalanche forecasting is still an art rather than a science. The variables that determine when conditions are ripe for the triggering of a slide are numerous and complex. It is difficult to measure the mechanical properties of snow samples with any precision even in the laboratory, because the characteristics of a sample can change rapidly while it is being handled. There are, however, significant factors that can be measured in the field: the density and thickness of the snow slab, the size of the load compared with the shear strength of the substratum, certain patterns of the snow structure. This structure can be examined by cutting pits through the layers or by plumbing them with instruments, and a trained observer can recognize danger signs such as an underlying layer of ice or of snow converted to depth hoar. With information thus obtained it is possible to predict quite accurately the probability of the occurrence of avalanches within given areas. It is not possible, however, to forecast precisely where and when a slide will take place, because of unknown variables such as the existence of creep tensions and the unpredictability of the various natural or man-made shocks (earth tremors, construction blasting or the like) that can trigger the fracture of a slab.

The kind of avalanche threat I have just described takes some time to mature: the formation of the slab and its preparation for release are products of aging, temperature changes and various other slow processes. Quite different is the "direct action" type of slab avalanche that develops during or immediately after an intense winter snowstorm. Given certain meteorological conditions, such a storm can produce avalanches of massive proportions. The conditions have to do mainly with the depth of the snowfall, the density of the snow and the action of the wind in piling and drifting the snow. The probability that an avalanche will develop can be forecast by means of relatively simple measurements made during the storm. The two most significant factors are the precipitation intensity (the amount of water, in inches per hour, represented by the falling snow) and the wind intensity. The combination of prolonged high precipitation intensity



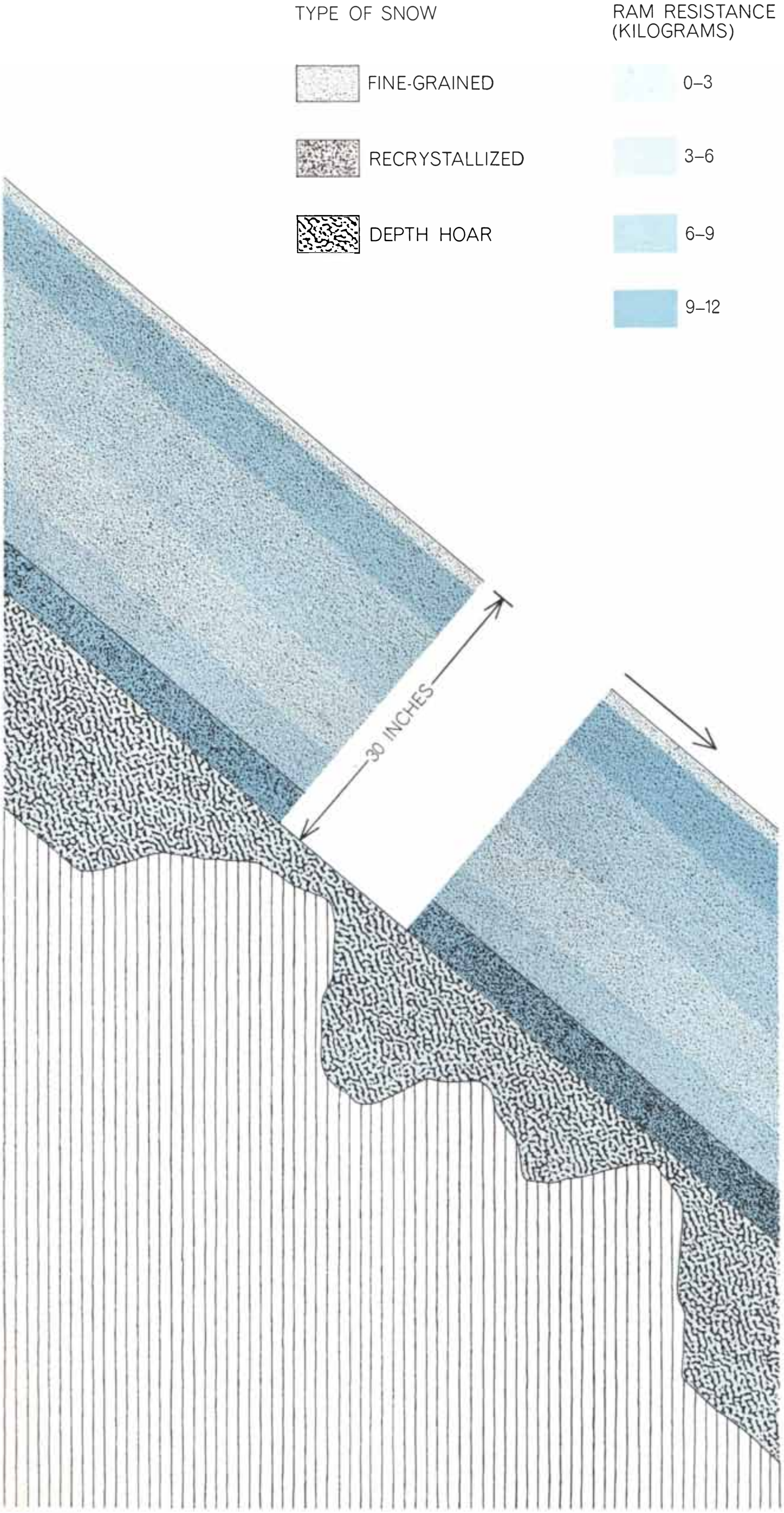
ing the terrain; several structures erected for that purpose appear in the background. The other calls for the artificial release of an avalanche so as to alter the conditions that might produce a more serious slide. Such a technique is illustrated by the puff of snow in the foreground, produced by the detonation of an explosive. The detonation has caused a slab of snow to fracture and begin sliding.

and high wind is almost always followed by a series of spontaneous avalanches.

Like river floods, snow avalanches constitute an annual phenomenon that varies in severity from year to year and can have catastrophic results. As in the case of floods, the necessity of defense against avalanches has long been recognized, and elementary methods of control have been practiced in the Alps for centuries. These measures have usually consisted in building a barrier of earth or masonry on the uphill side of a house with the object of diverting the flow of snow around it. Today there are available a number of engineering techniques for control of avalanches, some providing passive defense (protection against actual slides), others designed to prevent their occurrence. Complete and permanent control can seldom be achieved, particularly on large slide paths, but this ideal can be approached if necessity justifies the high cost. Such an investment usually will be made only for the safety of a large industrial installation, a major power-transmission line or a community of dwellings. Since avoidance is likely to be far cheaper than defense, modern practice is to locate new construction in carefully selected avalanche-free zones —if such zones exist in the area in question. When the problem is only a matter of protecting highways or other facilities used transiently, as it is in most mountain areas of the U.S., less costly methods may suffice. A relatively inexpensive program that reduces the avalanches falling on a highway by 90 percent may, for example, pay for itself by the savings in snow-plowing costs.

Fundamentally there are two different ways to prevent or control avalanches: (1) modification of the terrain and (2) modification of the snow, which includes the deliberate release of slides when and where they will do little or no harm. The first general method is expensive and requires continued maintenance, but it is reasonably permanent and offers maximum protection. The second is comparatively cheap but must be applied repeatedly, perhaps many times each winter. Modification of the terrain is usually chosen when the problem is to protect a large area or fixed installations; modification of the snow is employed most commonly for protecting highways and ski slopes. Let us consider first the techniques developed for terrain modification.

A naturally rough terrain provides good anchorage for the first snow de-



SNOW STRUCTURE conducive to the formation of a "slab" avalanche, in which a large mass of dense snow breaks loose from its position on a slope, is represented schematically as it appears at the point of fracture. The bottom layer consists of depth hoar, a recrystallized snow that provides a precarious foundation for any snow deposited on it. The next layer is made up of partly recrystallized snow; everything above that layer is fine-grained, wind-drifted snow. The numbers in the key refer to the ram resistance, a measure of snow strength that is obtained by driving a rod called a penetrometer into the snow vertically.

FRACTURE LINE of a large slab avalanche is conspicuous on the upper part of this slope. The avalanche slid on a layer of depth hoar next to the ground. Below the fracture line are a few blocks of the hard snow that made up the slab; they were arrested by rocks.

CRYSTAL STRUCTURE of snow has much to do with the likelihood that an avalanche will or will not start in a given area. At left are crystals produced by destructive metamorphism, a form of change in structure that rounds the grains and creates a snow that stabilizes and gains strength with age. At right are crystals of hoar produced in the lower depths of a snow cover by constructive metamorphism, which results in a fragile layer that provides an unstable base for later snowfalls and creates avalanche conditions.

posited on it; as the snow builds up, however, it buries the natural irregularities and becomes a smooth sliding platform for a slab formed on it. The really effective natural obstacles to massive snow avalanches are broken terrain, ledges of rock, stands of heavy timber, narrow gullies and abrupt changes from a steep slope to a gentle one. These features serve variously to prevent snowslides, inhibit their size, channel them into narrow paths or reduce their momentum. Most of the artificial structures built to control avalanches are designed with the same objectives in mind.

One of the simplest devices, long employed in the Alps, is a stone wall in the shape of a wedge to shunt the slide around a house [*see top illustration on opposite page*]. A tall, massive pylon of concrete will act in the same way to protect a power-transmission tower. To shield a wider area, a long wall of earth or masonry built diagonally across an avalanche path will divert slides in much the same way that a curving gully does. A barrier constructed straight across the path is less effective because the basin behind it may soon be filled by snow, and in any case a large, fast-moving slide will leap over the wall. To protect highways and railroads, sections of the road at the foot of steep slopes are commonly covered with strongly built snowsheds so that avalanches will flow over them.

Some 15 years ago engineers in Austria inadvertently discovered an effective form of construction to brake an avalanche. They had built some diversion structures in an avalanche path near Innsbruck, and at the end of the job they left some mounds of rubble nearby. The following winter the first avalanche was broken up by the mounds before it even arrived at the diversion structures. The mounds had arrested the slide by splitting it into crosscurrents that dissipated much of the kinetic energy of the sliding mass. The Austrians seized on this discovery to build systems of avalanche mounds, and since then several such systems have been constructed in the western U.S., Canada and Alaska to protect highways. An attractive feature of the mound device is its low cost: a barrier to avalanches can be built with a bulldozer simply by mounding up earth or rubble at the site. On the other hand, mounds are less effective with large, fast-moving avalanches of dry snow (which are partly airborne and so tend to flow over the mounds) than with avalanches that move mostly along the ground.

One of the most effective techniques for preventing major avalanches—designed to strike at the cause, so to speak—is the erection of snow-supporting structures in the areas where avalanches start high on the mountain. These structures anchor the snow to the mountainside, reduce or eliminate zones of stress within the snow and arrest any small slides of loose snow that may start within the area [*see bottom illustration on opposite page*]. Theoretically such a system can completely prevent dangerous slab avalanches, but in actuality this goal is difficult to achieve. Practical defense systems usually need to be strengthened or extended from time to time as nature attacks their weaknesses. The structures need not be as massive as the barriers built to divert a full-grown avalanche, but they must be strong enough to bear a heavy load. The forces involved are indicated by the fact that even a shallow snow cover can bend structural steel as it settles. The settlement, internal deformation and slipping of a snow cover on the ground generate

BREAKER MOUNDS serve to impede avalanches near the Trans-Canada Highway in British Columbia. Austrian engineers discovered the mound technique when they left heaps of rubble from the construction of other avalanche-control structures; the next avalanche was broken up by the mounds before it reached the other structures. Mounds are now built purposely for avalanche control.

forces that can add up to several tons of pressure per square meter.

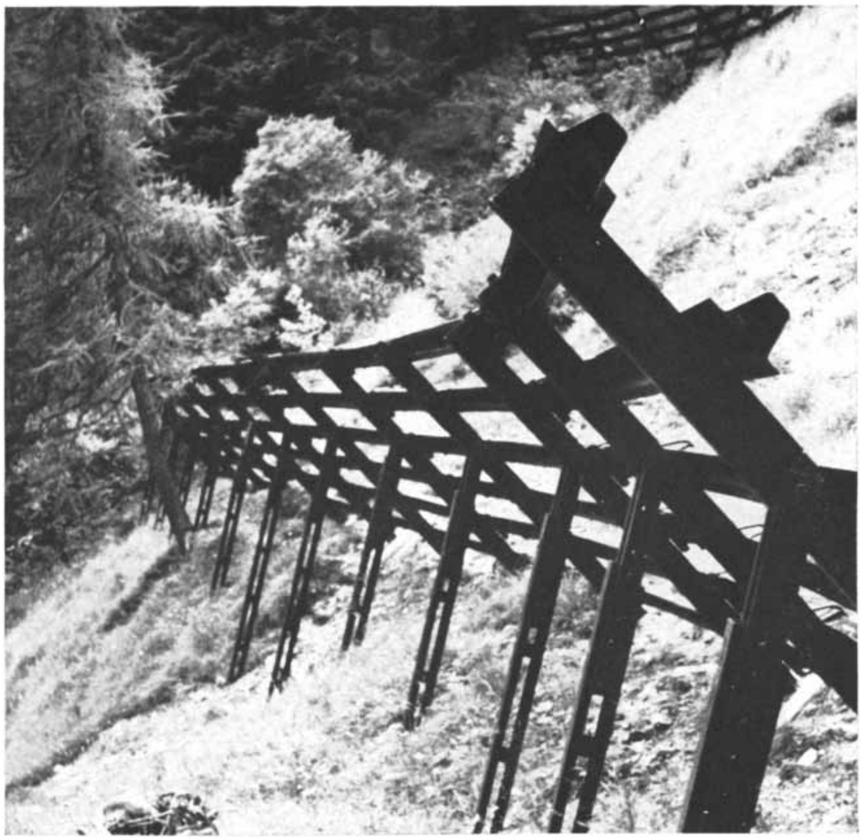
The structures designed to divert or withstand avalanching snow must be extremely strong. The thrust of avalanches against flat surfaces in their path has been measured as high as 100 tons per square meter. The materials generally used to build passive-defense structures are stone, reinforced concrete and combinations of these with earth fill. The active-defense, or preventive, structures entail the difficulty and cost of transporting heavy materials to high mountain sites. Efforts are now made to use steel, light metals and wood as much as possible; intensive engineering research has been done in Switzerland and Austria.

The Swiss Federal Institute for Snow and Avalanche Research has long been an international leader in the investigation of avalanche problems. It conducts studies in the basic physics of snow and ice, in snow mechanics, on the creep pressures that develop in slabs and on the design of defensive structures and techniques. For investigation of the forces involved the institute has built an artificial avalanche chute equipped with many measuring instruments. The chute, a metal-floored slide mounted on a trussed framework, can be tilted to various degrees of steepness. From a gate at the top, snow loads of a ton or more are released, and their impact against a catching plate is measured by strain gauges. This testing machine has shown, among other things, that sliding snow, because of its internal shear strength, generates an impact several times greater than does liquid water falling the same distance. The machine has turned up much information that will be useful in designing avalanche barriers and deflecting structures.

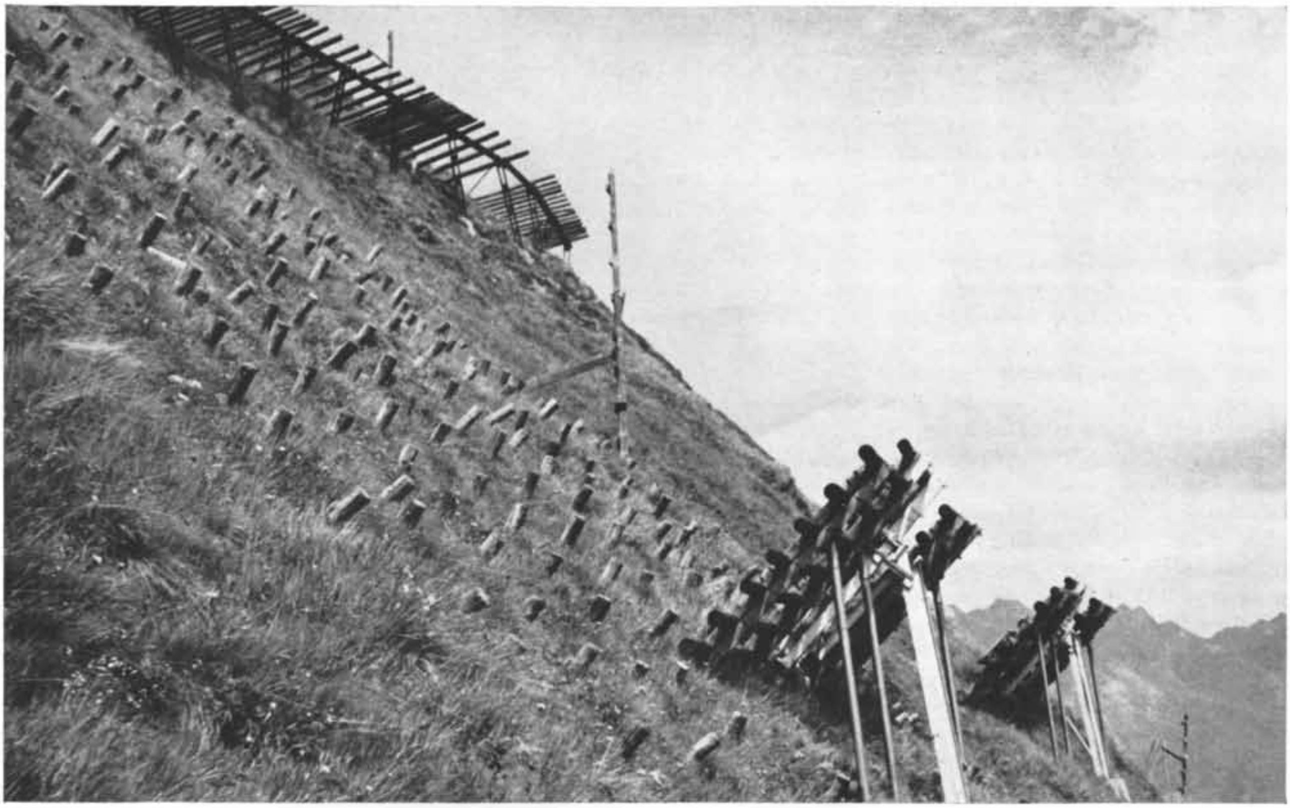
At the Federal Material Testing Laboratories in Switzerland, Adolf Voellmy has analyzed the effects of sliding snow on buildings. He has found that an avalanche often exerts a strong lifting force on a building in its path, thereby stripping off the roof or raising a frame building from its foundations. These findings suggest that the vulnerability of buildings to avalanches can be reduced by tying them more securely to their foundations.

Much of the recent research on defenses against snow avalanches has been directed to a search for simple methods of prevention. When all is said and done, the attempt to control avalanches by means of massive physical structures is an expensive and only

WEDGE TECHNIQUE, long in use in the Alps, involves incorporating a wedge on the uphill side of a building, as on this church near Davos, to divert a flowing mass of snow.



AUSTRIAN STRUCTURE was designed to prevent the formation of avalanches by helping to anchor snow. Made of steel and about 10 feet high, it is located near the Brenner Pass.



EXPERIMENTAL INSTALLATION on the Dorfberg at Davos is aimed at providing support for a body of snow and hence deterring avalanches. The two lower structures have instruments to measure the pressure of the snow. Effects of the pressure are reduced by the field of short posts around the nearer structure; these posts inhibit the sliding of a snow cover over the wet grass. The upper fence, with horizontal posts, has vertical supporting beams with different spacing; its purpose is to test the effects of the spacing.

WIND BAFFLES constitute another experimental array in Switzerland. They were built to create an irregular flow of wind in an area where a steady flow tends to build up a slablike mass of snow. Such a slab, if it breaks loose, can form a dangerous type of avalanche.

partly effective strategy. A barrier that breaks up or diverts a slide of snow along the ground cannot offer much protection against the rush of a great snow cloud or wind blast, which may cross a valley from one side to the other. Moreover, the expensive structures for preventing the start of avalanches cannot be built in all the places where important hazards exist. Less expensive techniques, therefore, are continually being sought.

One recent innovation, still largely in the experimental stage, is the use of wind baffles to channel the distribution of snow during a storm so that the snow will not form a large slab. The baffles, usually made of wood, are arrayed to face the prevailing storm winds, with the object of breaking the wind flow into an irregular pattern that will cause the snow to be deposited in clumps—deep drifts alternating with intervals of shallow snow or even bare ground. Tests have indicated that the baffles may be effective in certain climates if they are placed in a sufficiently dense array, but the method has not been widely adopted.

We are led then to the possibilities of preventive action on the snow itself, designed to forestall any large or destructive slide. One of the oldest and simplest strategies is the artificial triggering of small avalanches before the potential for a large one has developed. Properly applied, artificial release can bring down piecemeal the snow load deposited along a path where avalanches are likely to occur. Furthermore, in any circumstances the deliberate release of the snow at chosen times makes it possible to give adequate warning and see that the danger zone is cleared.

One of the important dividends from this practice has been the educational effect on the public. Comparatively few people, after all, ever see a natural avalanche; most of the slides fall during storms and many of them occur at night. The avalanches artificially released by the U.S. Forest Service in western ski areas in recent years, however, have on occasion been witnessed by large crowds. A big slab avalanche thundering down a mountainside in bright sunlight, sweeping heavy timber before it and raising an immense cloud of snow dust, is one of nature's most spectacular performances. Anyone who sees it gains a new respect for the power and danger of sliding snow. These public demonstrations of artificially triggered slides have improved the response to signs warning people to avoid dangerous areas.

The artificial release of avalanches is usually achieved by detonating explosives at the tension zone of a slab. Artillery fire is the safest and most effective method of cracking a slab that is ready to be released, and these operations no doubt have given many people the impression that avalanche control consists mainly in artillery battles with mountains. Actually it is not always a release of an avalanche that is sought; an explosion can also test the condition of the snow and often has a stabilizing effect even when no avalanche falls.

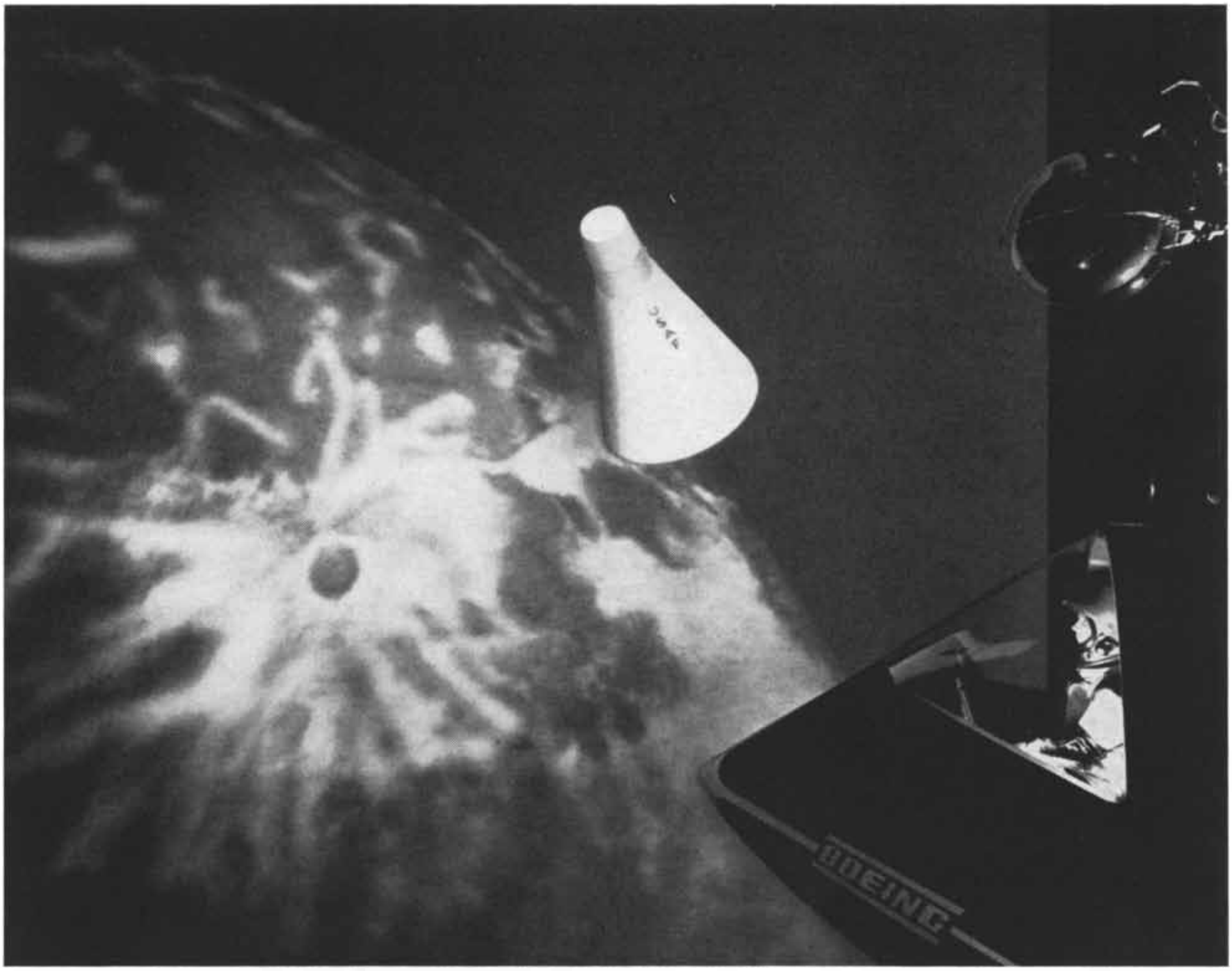
The Swiss originated the artillery technique by firing mortar shells into the snow. In the U.S. and Canada the preferred weapons are recoilless rifles and mountain howitzers, because of their longer range and the greater ease with which they can be fired accurately. The release of an avalanche requires at least a 75-millimeter shell; where possible, 105-mm. weapons are used. Because armor-piercing shells or high-angle firing (as from a mortar or howitzer) may penetrate too deeply into the snow and sometimes result in duds, the most effective weapon is a flat-trajectory cannon firing shells equipped with fuzes that will detonate them at the snow surface. A compressed-air cannon similar to a baseball pitching machine, developed by experts in the Forest Service in cooperation with a manufacturer of such machines, is currently being tested. This "avalauncher" is capable of pitching a two-pound explosive charge up to 2,000 yards. Because the explosive does not throw out fragments of steel shell-casing, the device is expected to replace artillery for use within the avalauncher's range.

The Forest Service has been using artillery for controlled triggering of avalanches in western ski areas since 1952. It has proved to be a relatively inexpensive and successful method of avalanche control for protecting ski slopes and mountain highways. At the same time much research has been done on techniques for striking directly at the causes of instability in snow by modification of the snow.

In theory it should not be difficult to strengthen snow and stabilize it. Snow is a substance particularly sensitive to alteration by mechanical disturbance and other treatments. Compacting it or even simply shaking it will initiate sintering, or cementing, of the bonds between crystals so that the snow hardens in a matter of hours—a process known as age-hardening. The compaction of snow has indeed been a useful practice. Obviously this is not a practicable program for an avalanche path covering a wide mountainside, but it is feasible for short paths or critical spots where large avalanches are most likely to start. In some places the packing caused by skiers sliding repeatedly over the snow (a man on skis provides a pressure of about 50 grams per square centimeter) is sufficient. Where a layer of depth hoar has developed under the surface this pressure is not enough, but such a layer can be strengthened by intensive foot-packing; the pressure of a stamping boot is more than 300 grams per square centimeter. In some ski areas where layers of depth hoar are likely to form it has become common practice to march groups of men back and forth over the early-season snowfalls on the critical stretches of avalanche paths to stabilize the snow against later constructive metamorphism.

One of the most efficient techniques, in terms of the small amount of energy required, is an operation on the slab layer. This consists in breaking up the slab, with the aim of relieving the stresses of creep tension and thus allowing the slab to settle and establish a firm bond to the underlying base. Sometimes a few ski tracks cut through the soft snow suffice to prevent the formation of a continuous slab. To break up a hard slab after it has formed the Forest Service uses charges of explosive in selected places. Often blasting done to release an avalanche artificially will provide a stabilizing effect by cracking a slab and relieving creep tension even when no slide actually occurs.

R. M. Stillman and I, working together for the Forest Service, have been investigating a new approach to the treatment of snow. Its object is to prevent the formation of layers of depth hoar, a major cause of large avalanches in the Rocky Mountains and elsewhere. This approach looks to the modification of snow by chemical rather than mechanical means. It has been known for some time that certain organic molecules poison the growth of ice crystals. When these molecules in the vapor state attach themselves to the crystals, they cause the crystals to grow in odd shapes. In our laboratory we found that selected organic substances, principally hydrocarbons with long-chain molecules, had certain inhibiting effects on crystals growing by sublimation. In the presence of 2-octanol in vapor form, for instance, the ice crystals grew in the shape of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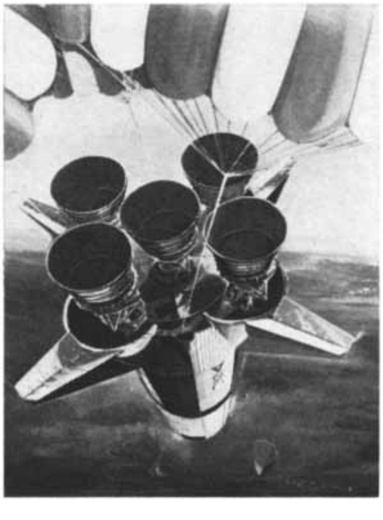
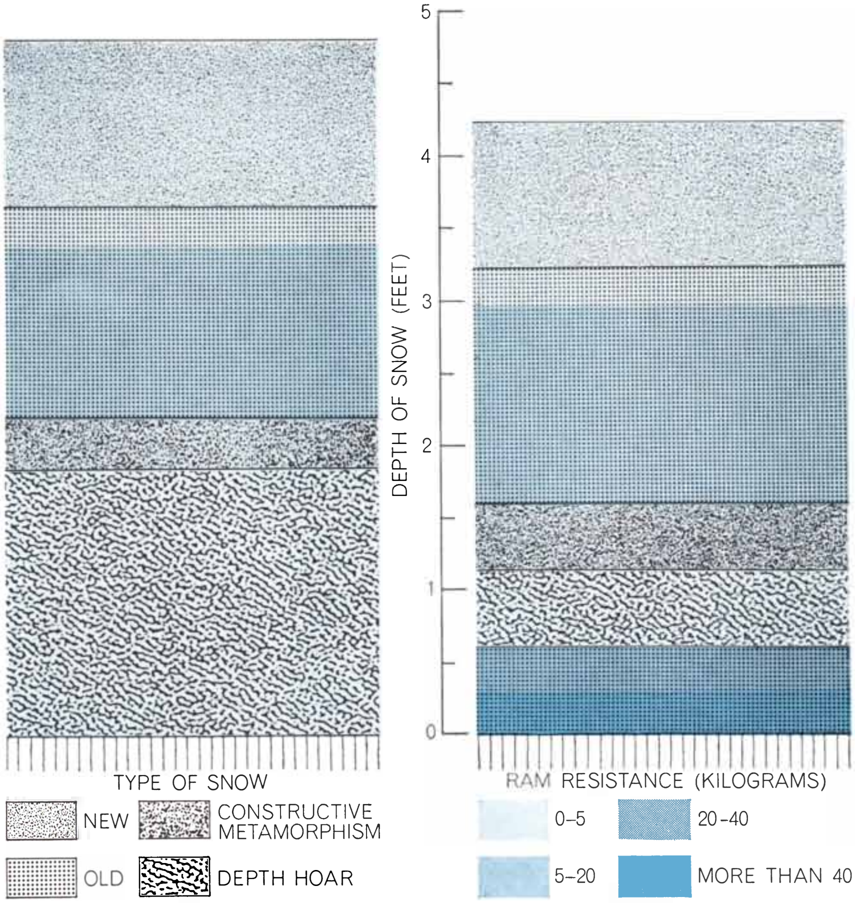




CHEMICAL TREATMENT designed to prevent avalanches produced the changes of structure shown in a comparison of undisturbed snow (*left*) and snow that has accumulated on a plot of ground that was sprayed with benzaldehyde before the first snowfall (*right*). The undisturbed snow has an unstable layer of soft, fragile depth hoar at bottom. In the treated plot vapor from the chemical has inhibited the formation of depth hoar and created a bottom zone of snow that is much harder than would be expected in a natural snow cover.

long, slender needles. Presumably the organic molecules attached themselves to particular sites on the ice crystal and blocked the attachment of water vapor molecules to the crystal in certain directions of growth. We then found that some organic molecules, notably benzaldehyde and N-heptaldehyde, severely inhibited along all crystal axes the growth by sublimation.

It took only trace amounts of these chemicals to produce the effect. Suppose the chemical was sprayed on snow. Would it prevent the formation of depth hoar, which normally grows by the accretion of sublimated water vapor on snow crystals? Laboratory and field tests showed that the introduction of small quantities of the chemicals in snow did in fact severely inhibit or completely prevent the development of depth hoar. The process was most effective when the chemical was sprayed on the ground before the first snowfall of the winter. A few grams of chemical per cubic meter of snow was enough to block any development of depth hoar in the bottom snow up to about 15 centimeters above the sprayed ground surface [*see illustration above*].

We proceeded then to a further field test, to see if chemical treatment could prevent avalanches in a path where depth hoar and slab fractures commonly developed. We chose a small avalanche path at Berthoud Pass in Colorado and sprayed it with ethylene glycol (the common antifreeze for automobile radiators), which is not as strong an inhibitor of hoar as the aldehydes but is much less toxic. The results of this first full-scale test were inconclusive. No avalanche occurred in the test path that winter (1963–1964), although several fell in paths nearby. We found, however, that a substantial amount of depth hoar did develop in the test path, and we judged the snow to be dangerously unstable. Nonetheless, the chemical approach looks promising enough to encourage a thorough investigation of its possibilities.

SCIENTIFIC NUMISMATICS

Ancient coins have provided much information about the sites in which they were found and about the societies that produced them. They can be made to yield even more information by modern statistical methods

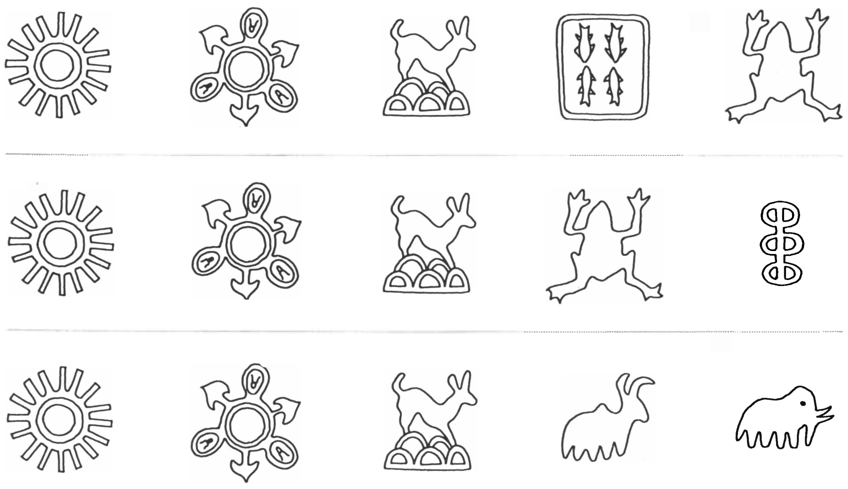
by D. D. Kosambi

The term "numismatics" is normally associated with the avocation of collecting coins. It is well known, of course, that the study of coins also plays an important role in archaeology. Here I should like to set forth in general terms a mathematical approach that can make numismatics more of an exact science. With this approach the archaeologist can add a degree of precision to his study of coins, and modern governments can improve the procedures with which they control their coinages and even their paper currency.

The archaeologist finds coins useful because they are normally issued by a governing authority and hence constitute a form of official document. The archaeological value of coins arises from the fact that they survive to an extent unmatched by most other documents, both because they are physically durable and because they have value for the members of the society and so are likely to be put away in hoards. As a result coins have revealed the existence of cities and even kingdoms that are not mentioned in the old literary histories.

Even when an ancient society is known from other sources, coins can be helpful in various ways. Dated coins—or those that can be otherwise identified with a particular epoch—help the archaeologist to fix the age of the level in which he is digging, to organize the chronology of rulers and to establish the dates of events commemorated by certain coins. The designs on coins reveal something of the society's religion or mythology and reflect the evolution of its art. Often the only indication of what prominent persons of ancient times looked like is provided by the portraits on coins.

This kind of information is obtained from coins by the scientific techniques of description and classification. A somewhat more complex scientific procedure involves assaying the metallic content of a coinage over a long period of time in order to obtain information about the economic history of the society. Such an investigation reveals that the French sou, which is today a synonym of worthlessness, began its career as the solidus, a gold coin of the emperor Constantine the Great [*see illustration on page 105*]. This coin's steady degeneration through 16 centuries is a considerable tale in itself. Similar work shows that the gentle art of inflation was practiced just as ably in antiquity. Plutarch says, and archaeology confirms, that Solon the Wise reduced those Athenian debts that he did not cancel altogether by making them payable in drachmas debased by 27 percent.



FIVE-MARK SYSTEM was found on the obverse (heads) side of most coins in a hoard unearthed in 1924 in the ruins of Taxila, an ancient Indian city. In each set of five marks the first four represented a king; the fifth, an issuing authority such as a crown prince. Often the fifth mark in one set became the fourth in another, indicating that a son had succeeded his father as ruler. The marks were helpful in establishing the chronology of the coins.

The mathematical approach I have in mind goes beyond the scientific procedures I have described so far. The basic theory that makes such an approach possible was developed only a generation ago. This theory, known as "the homogeneous random process," applies to numerous different types of natural phenomena that are under the influence of many factors of a random nature, for example the diffusion of molecules of one substance through the molecules of another substance, the unceasing zigzag movement (called Brownian motion) of small particles suspended in a fluid, and even the behavior of a stock exchange.

As applied to numismatics, the theory embraces several factors relating to the weight of coins. In antiquity it was easier to control the weight of coins than the alloy. The reason was that, given a good pair of balances, anyone could

PUNCH-MARKED COINS of ancient India, similar to those found in the Taxila hoard, are depicted. On the obverse side (*left*) some features of the five-mark system shown in the illustration on the opposite page are visible. The reverse side (*right*) of such coins was either blank or carried a different system of individualistic punch marks. These coins and those in subsequent photographs are in the collection of the American Numismatic Society. In all the photographs the obverse side is at left and the reverse side is at right.

weigh the coin quickly and accurately, whereas an assay of the metallic content of the coin called for an expert. Hence the weight of a society's coinage tended to remain fixed even when the coinage was systematically debased in metallic content.

Yet no matter how carefully coins are struck in one minting, by the same craftsmen using the same technique, there is an unavoidable variation in their weight. This variation is restricted somewhat by the traditional practice of melting down the coins that fail to come within a certain margin above or below the "true" weight. The amount of tolerance allowed has been termed "the legal remedy." In India before World War II, for instance, the legal remedy was 1/200 of the weight for the standard coin: the rupee of silver alloyed with 1/12 copper and weighing 180 grains. The differences in weight of carefully minted coins can be determined only with very delicate balances.

When a coin is put into general use, it loses a tiny amount of weight whenever it is involved in a transaction. Mechanical abrasion removes a bit of the coin, and the metal is also subjected to the chemical action of various common agents, including the acids produced by the glands of human skin. In short, the coin loses weight by wear. Such losses would vary from coin to coin even if every coin were handled in practically the same way. The fact is, of course, that not every coin put into circulation at one time is handled in the same way over the years, and so the variation among coins is increased.

The net effect of all these variations

in weight, from both minting and wear, can be dealt with by the mathematical theory of the homogeneous random process. The result of the application of this theory to a set of coins in circulation is reflected in the three curves in the illustration on page 107. The first of them, denoted *A*, is the familiar Gaussian curve of normal distribution; it reflects the fact that a group of coins minted by some uniform process has such a normal distribution of weights. The distribution is truncated because coins weighing more or less than the tolerated margin of error have been excluded by the application of the legal remedy, but in practice the resulting deviation from a normal distribution is negligible unless the minting has been singularly slipshod.

After the coins have been in circulation for a time, the curve of weight distribution is still normal but has changed shape, as is apparent in curve *B* in the illustration. The middle of the curve has moved to the right, indicating that the average weight of the coins has decreased, and the curve is flatter, showing that the variation in weight among individual coins has increased. The decrease in the average weight and the increase in the variation are each strictly proportional to the length of time the coinage has been in circulation.

As time goes on the center of the curve moves steadily to the right from the loss of weight. The average weight declines regularly because the average loss of weight is the same per unit of time, say a year. The curve becomes flatter much more rapidly, however, because the square of the standard deviation increases regularly with time. The standard deviation is the distance from the center of the curve to the point on either side where the curve begins to bend the other way. Curve *C*, reflecting a considerable period of circulation for

DATING OF HOARD at Taxila was made possible by the presence of coins such as these. At top is a coin of Alexander the Great, who invaded India in 327 B.C. At bottom is a coin of his successor, Philip Arrhidaeus, in whose brief reign few coins were issued.

a coinage, shows the mean weight to have declined further and the variation in weight to have increased so much that only half of the distribution can be portrayed.

Thus far I have described a situation involving a single group of coins minted and put into circulation at the same time. Suppose one were to take from circulation a random sample of coins of the same denomination, alloy and mint weight but of different date. The curve showing the distribution of weight in the sample would be asymmetric with a long tail to the right, reflecting the fact that the older coins have lost more weight than the newer ones. The shape of such a curve can be calculated theoretically, given the proportion of coins of each minting together with the general rate of wear and the rate of increase in variation in weight among individual coins. These three constants cannot be predicted theoretically; they must be obtained by observation for each country and each denomination of coin.

There is one more factor that must be considered; I have termed it "absorption." Coins of a group tend to disappear from circulation in a regular way that is proportional to the number circulating, provided that the rate of disappearance is not affected by some abnormal situation. The rate of absorption is represented by a statistical law—the same law that applies in the familiar geometric progression (2, 4, 8, 16 and so on). This is also the law of absorption for radiation, the simplest law of biological mortality, the law for the healing rate of wounds and the law of growth by compound interest.

Certain conditions have to be met if these mathematical principles are to be applied successfully. The coins must have been minted accurately enough to show only a slight initial variation in weight. If this is not done, as

DEBASEMENT OF COINAGE is typified by the gradual transformation of the solidus (*top*), a gold coin of the emperor Constantine the Great, to the French sou (*bottom*). At one time "sou" referred to the five-centime piece; it now means any coin of little value.

SLOW ACCUMULATION of coins in a hoard renders inapplicable the mathematical approach to numismatics. Such an accumulation is the "Peter's pence" collection at the Vatican, consisting of Anglo-Saxon coins such as this one from the reign of King Offa of Mercia (eighth century A.D.). Pilgrims' donations built the collection over many generations. The mathematical approach needs coins that have had comparable histories of circulation.

was often the case with ancient coins of the less valuable metals such as copper, pewter and billon (gold or silver heavily alloyed with a base metal), the effect of wear on the weight distribution is blurred. Secondly, the circulation of the coins must have been normal enough to have the proper effect. This condition usually excludes gold coins, which are often hoarded with a minimum of handling and are also likely to be clipped by owners seeking to amass a private store of gold. Finally, a sample to which the mathematical principles are to be applied must consist of a fairly large number of coins with comparable histories. Ideally they should be from a common hoard. In keeping with this condition it is useless to compare similar coins of widely divergent histories. For example, a coin of the Greek adventurer Menander, who founded a kingdom in India about 125 B.C., turned up in a bazaar at Poona in 1942 and was accepted as currency; its history was plainly different from that of Menander coins dug up by archaeologists in various parts of India or that of a specimen found in Wales.

Even if one has access to a hoard that fulfills all these conditions, it is necessary that the hoard be reasonably well preserved so as to be free of encrustations that would produce variations in weight unrelated to the variations attributable to circulation. If a hoard of coins made of a silver-copper alloy has been buried in damp soil (as happens more often than not in India), the moisture slowly draws the copper to the surface of the coins, leaving a spongy silver underneath. Some Indian numismatists have proceeded to strip away the copper on the technically impossible supposition that molten copper had been poured onto the silver to bring up the weight of the coins.

Some years ago I was fortunate enough to have access to a hoard that met all these conditions. It was a collection of about 1,150 pieces of silver found in a bronze jar that archaeologists had dug up in 1924 in the ruins of Taxila, an ancient Indian city in what is now Pakistan. The jar and the dry climate had preserved the hoard from damage. It was possible to date the hoard approximately by the presence of an unworn coin of Alexander the Great, who invaded India in 327 B.C., and to date it more precisely by a mint-condition coin of the emperor who briefly succeeded Alexander—his half brother Philip Arrhidaeus. The condition of the coin, taken together with the facts that Arrhidaeus issued few coins and that Taxila was far from his actual domain, justifies the assumption that the coin found its way into the jar soon after issue. The hoard can thus be dated close to 317 B.C., when Arrhidaeus was imprisoned and assassinated. There was nothing in the archaeological context to indicate that the hoard had been deposited slowly over a long period of years, as is the case with religious deposits such as the "Peter's pence" collection at the Vatican, consisting of donations left annually by generations of Anglo-Saxon pilgrims. Therefore it seemed reasonable to assume that the Taxila coins had had a comparable history of circulation and that this history had come to an end at about the time Alexander's local successor Seleukos Nikator lost Taxila to an invading army from the east.

Beyond this the coins at first yielded little information. Most of them had on their obverse (heads) side five punch marks with much in common from coin to coin. The reverse (tails) side in many instances had an entirely different system of much smaller punch marks. Nothing else was readily evident. The hoard therefore presented a difficult problem of classical numismatics: the arrangement of unidentifiable coins in their proper chronological order. It was in addressing myself to this problem that I began to work out the application to numismatics of the mathematical principles I have described.

By way of background to the story of my investigation it will be useful to describe briefly the historical setting of India in the period to which the hoard is ascribed. Alexander, whose army was reluctant to follow him farther in his effort to conquer Asia, retreated from India soon after invading it. After his departure a Hindu king, Chandragupta (called Sandrocottus in Greek records), extended his rule over the entire northern part of the Indian subcontinent, expelling or destroying the Alexandrian garrisons. Chandragupta established the seat of his empire at the capital of the kingdom of Magadha in what is now the Indian state of Bihar. Thus was founded the dynasty called Maurya, which lasted from 312 to 178 B.C. The most illustrious figure of the Mauryan dynasty was Chandragupta's grandson Asoka, who reigned for many years, expanded the empire as far west as the Greek kingdom of Bactria and by supporting Buddhism gave it a powerful impetus in India.

In the immediate pre-Mauryan period the only royal authority strong enough to issue coins on a large scale was the Magadha kingdom. In fact, it is evident from a comparison of the punch-marked coins of the Taxila hoard that they are of the type found in profusion in Magadha and wherever Magadhan influence penetrated. The system of five marks on the obverse side of the Taxila coins is the same as that of the Magadhan royal coinage [*see illustration on page 102*]. The first four marks represent a king; the fifth, an issuing authority such as a crown prince or provincial governor. Often the fifth mark in one series becomes the fourth in another, indicating that a son had succeeded his father.

These marks made it possible to group the coins. Then the average weight of each group gave its relative chronological order. It might also be thought that the marks would make it possible to set each marking system opposite the name of a king and thereby solve the whole problem of chronology. The difficulty here lies with the limitations of Indian historical records. There are no known or decipherable royal inscriptions before Asoka. The records of the Jains, the Buddhists and the Brahmans often call the same kings by different names. In any case the names of kings usually appear in such records almost incidentally, as part of the inflated, semimystical story of some religious figure such as the Buddha. There is no mathematical theory for this kind of history.

Considerably more useful were the punch marks on the reverse side of many coins. These marks, unlike those on the obverse side, bore little resemblance to one another. They showed all the individuality of the ticket punches used by conductors on American railroads. A group of coins with identical obverse markings might include some specimens with blank reverse sides and some with from one to more than 20 of the tiny reverse marks. (When the number rose above 20, the marks were difficult to count.)

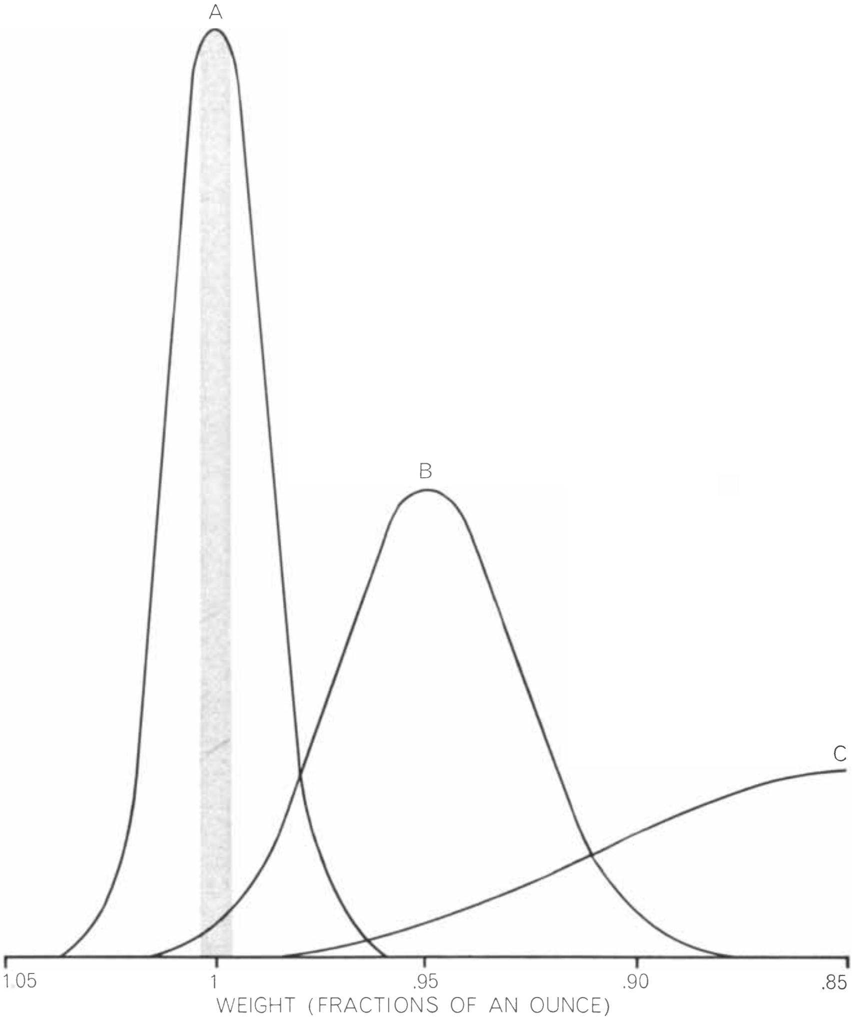
If one ignores the obverse side and merely groups the coins according to the number of marks on the reverse, a striking fact emerges: the larger the number of marks, the lower the average weight of the coins [*see illustration at left on next page*]. In other words, the reverse marks supplement the loss of weight as a sign of age. Evidently the reverse marks were correlated in some systematic way with the circulation of the coins.

These marks indicate a system of regular checking of the coinage, probably by traders' guilds. The traders were simultaneously financiers, bankers and dealers in precious metals; they would have had good reason to assure themselves that a given coin continued to adhere to a standard of weight. Presumably the checking was done at more or less regular intervals, apparently about every 12 years, indicating that the practice began about 500 B.C.

Both the obverse and the reverse marks were valuable as corroborative evidence when I undertook to check the weight, variation and absorption rates of the Taxila coins. Interestingly enough, about 95 percent of the coins fell in the range of some very accurately cut stone weights found in the excavations of two cities much more ancient than Taxila: the cities of Mohenjo-Daro and Harappa in the valley of the Indus River. This great civilization, comparable to that of Sumer and probably contemporaneous with it, had vanished without apparent trace until it was revealed by digging in 1925. Yet in spite of the complete silence of all Indian tradition on the existence of the earlier civilization the weight standard of the Indus valley survived unchanged into Mauryan times.

The weight curve of the Taxila hoard has the expected distribution with a tail to the right. Moreover, the number of coins compared with the number of reverse marks follows closely the theoretical "absorption" curve [*see illustration at right on next page*]. About 70 percent of the coins survived after each checking period, however long that period was. These observations suggest two things about the economy of Taxila: (1) it was stable for more than 200 years, as indicated by the regularity of circulation reflected in the curves of weight loss and absorption of the coinage, and (2) the balance of trade ran in favor of Taxila, as indicated by the presence of Magadhan coins in the community—coins that could only have come in payment for goods originating in or shipped through Taxila.

The same Taxila mound in which the hoard I have described was found yielded another hoard that was deposited at a higher level and hence was associated with a later time. The coins looked cruder. The system of obverse marks remained but the reverse marks had disappeared. Although these coins were almost in mint condition, the variation in weight was decidedly larger than that in the blank-reverse (and therefore little-used) coins of the earlier



DISTRIBUTION CURVES depict the history of circulation of a group of coins carefully minted and put into circulation at the same time. Curve *A* is high and narrow, indicating that most of the coins (a preponderance represented by the gray band) are close to the "true," or mean, weight. After a period of circulation (*B*) wear has caused the mean weight to decrease and the variation in weight from coin to coin to increase, an increase shown by the flattening of the curve. Further circulation augments these effects (*C*): mean weight is lower and variation has increased so much that only half of the distribution is shown.

hoard. In addition, the alloy was notably debased.

This second hoard was dated to about 250 B.C. by a coin of the Greek king Diodotus I, king of Bactria. Thus the punch-marked coins of the hoard were contemporaneous with Asoka. Although his coins had never been identified until these new methods pinned them down, it was known that his empire was prosperous and spread over the whole of modern India and Pakistan and most of what is now Afghanistan. The architecture and sculpture of the age were outstanding. Why, then, should the coinage be crude? Was there perhaps some mistake in my theoretical approach?

I was able to answer these questions by considering Indian currency that was in circulation in 1940 and 1941. At that time the rupee was still silver, but its copper content had been raised from a twelfth to a half. Moreover, the legal remedy had been abandoned. Although the same mints and machines had fabricated both prewar and wartime coins, I was able to pick out new rupees in 1941 that were above the standard weight by more than twice the old tolerance limit. Obviously Asoka's empire had been short of currency for everyday use, as the government of India was during World War II. Silver currency in both periods was progressively debased, although the ancients—unlike the wartime regime of India—never resorted to tokens and had no paper currency.

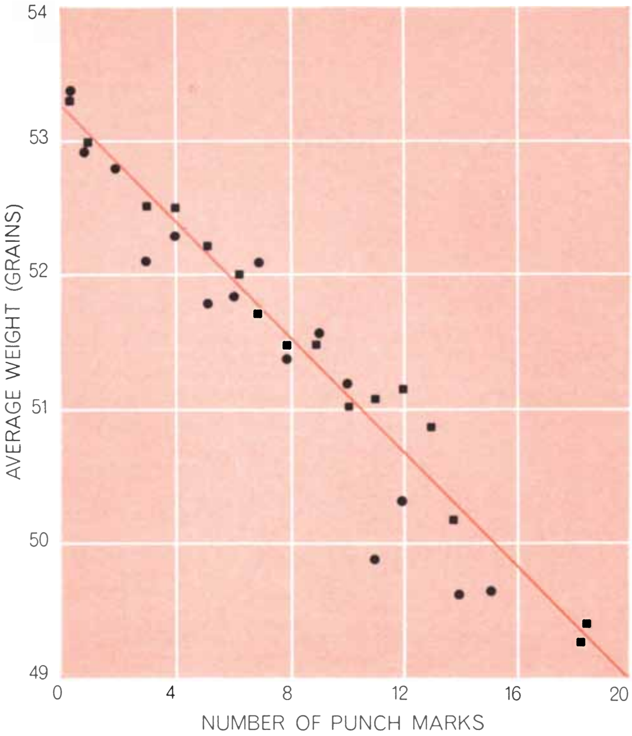
Having developed my idea of applying mathematical theory to the study of coins, I tested it with coins that were circulating in India in 1940 and 1941. Much of this work was drudgery; it took me about three minutes to weigh each of some 7,000 coins on a slow analytical balance. The tedium was somewhat relieved by the fieldwork involved in obtaining a representative sample of coins from active circulation. Except in three readily explainable cases, the weighings produced curves that closely fit the theoretical curves.

The first exception had to do with gold sovereigns. They had not been legal tender since 1931, although they did change hands occasionally between hoarders. Even so the fit would have been good had it not been for the two oldest pieces, which had been used only for worship by the family that lent them for weighing. Placed in front of the family's image of Lakshmi, the goddess of wealth, the two sovereigns had remained untouched for two generations.

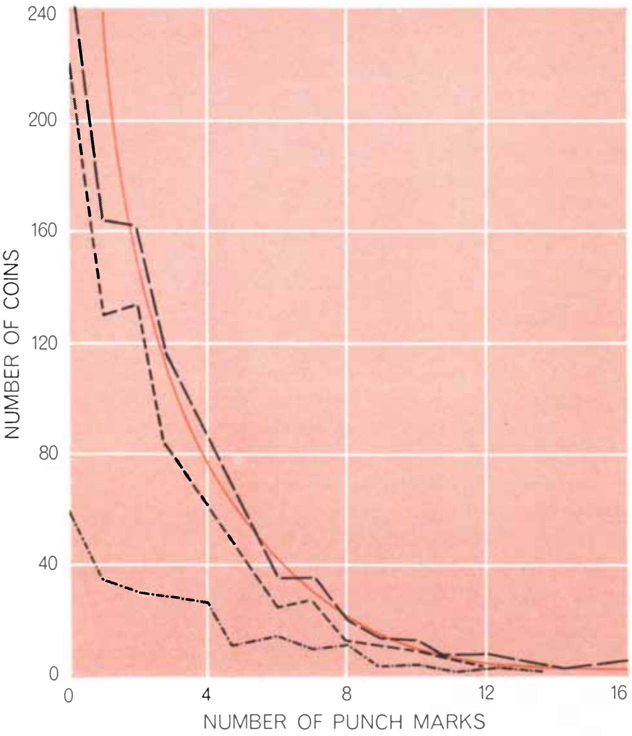
Another exception was the humble copper pie, which was then worth 1/192 rupee and could be found only in a few places such as Benares, where pilgrims distributed them as "charity" to beggars in order to gain merit at the lowest possible cost. The friend who had supplied me with 1,000 pie coins did not have the patience to take them all from the marketplace; he supplemented those that had been in regular circulation with a large number from a bank vault, where they had lain unused for years.

Thirdly, the anna pieces were of soft metal and in common use. Hence they wore more rapidly than any other Indian currency. Wear made it impossible to read the dates on some of the annas, and these pieces had to be removed from the sample. They were the most worn and therefore the oldest coins; they were also the lightest, and their removal from the sample raised the average weight of the rest of the sample.

The mathematical approach to numismatics has applications beyond archaeology. In this age of vending machines, pay telephones, turnstiles and whatnot the rate of wear of metal cur-



AGE AND WEIGHT of coins in the Taxila hoard are closely correlated. The punch marks were put on the back of the coin periodically for checking purposes; hence the more punch marks, the longer the coin was in circulation. The average loss of weight of the coins, resulting from wear, is shown by the diagonal line. Square and round symbols represent square and round coins.



ABSORPTION OF COINS, meaning their loss from circulation for various reasons, shows a close correlation with the number of punch marks found on the reverse side of the coins in the Taxila hoard. The theoretical curve of absorption is shown in color; the broken curve closest to it represents all the punch-marked Taxila coins. Other curves represent square and round coins in the hoard.

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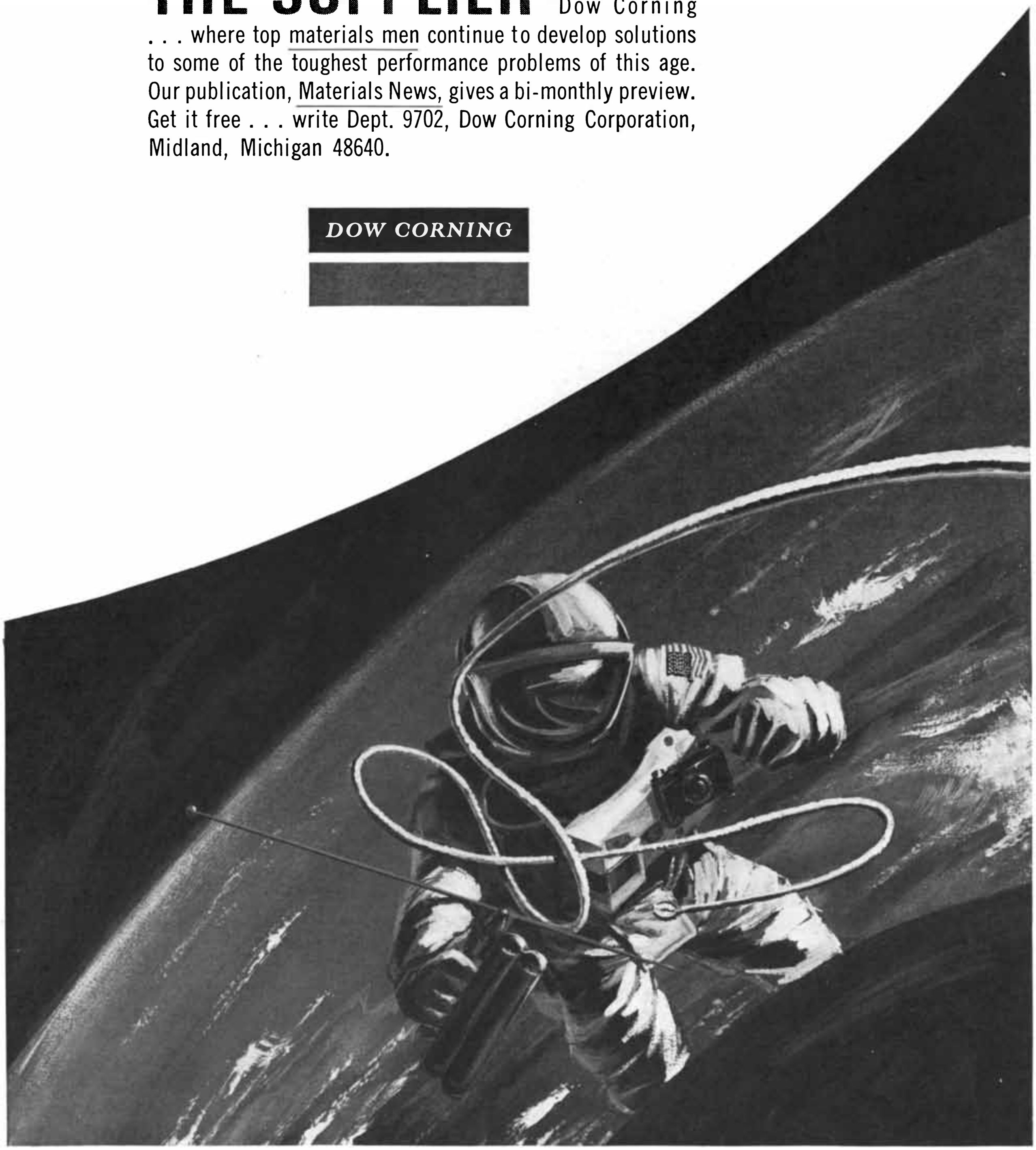

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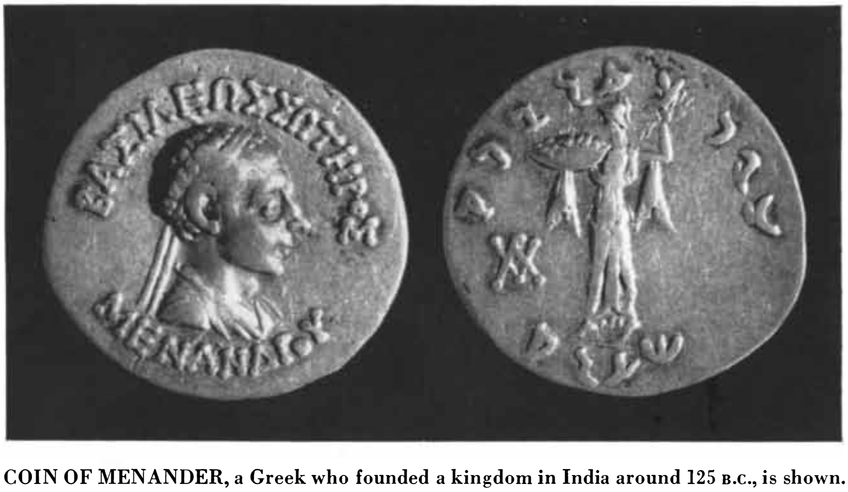
SECOND TAXILA HOARD was dated approximately by the presence of a coin such as this one from the reign of Diodotus I, who was king of the Greek kingdom of Bactria in about 250 B.C. Hence the second Taxila hoard was deposited about 75 years after the first.

rency could readily be determined by weighing samples, preferably on a much larger scale than my own modest efforts. Given the rates at which weight decreased and variation increased, and the weight limit below which a coin would be regarded as useless, the rate of replacement for every denomination could be calculated and the necessary replacement coins minted on a systematic schedule. Allowance would have to be made for changes in demand, such as those resulting from new consumer products and from population growth, and for loss of coins.

A second application would be to keep track of the number of coins in active circulation. This can be tested by the same procedure used to estimate the fish population of a lake. The fish are caught in a net, tagged and thrown back. The number of recaptures is plotted against the total catch; a simple formula then allows a calculation of the population. This number, of course, represents not all the fish but all the fish that are susceptible to the particular method of capture.

The "netting" of coins could be done by sampling post offices, banks, vending machines and stores on a certain day throughout the country. Tagging might be done by making the coins harmlessly radioactive. Then the recapture could be detected by a Geiger counter. A similar procedure would make it possible to estimate the amount of paper currency in active circulation. The tagging could be done through the serial number, which a computer would read by electronic methods. The same computer would be programmed to provide an estimate of the total currency in circulation. By these methods a scientifically minded treasury could decide on the basis of wear and loss whether it was better to issue coins or paper for any given denomination.



COIN OF MENANDER, a Greek who founded a kingdom in India around 125 B.C., is shown. A similar coin turned up in the marketplace at Poona in 1942 and was accepted as currency. Such a coin could not be used in a mathematical approach to numismatics because it would have a history of circulation widely divergent from that of other coins of similar origin.

MATHEMATICAL GAMES

Recreational numismatics, or a purse of coin puzzles

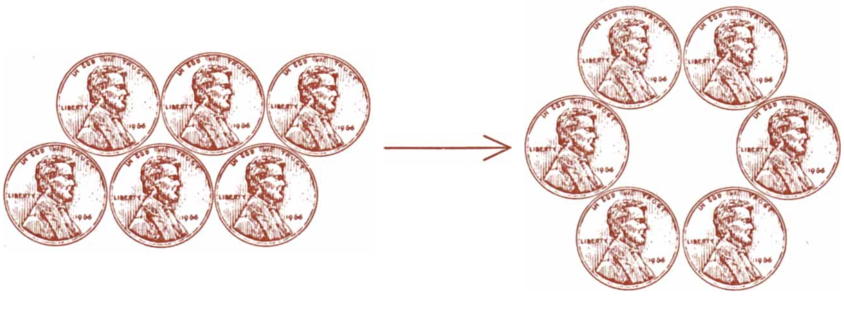
by Martin Gardner

In the preceding article D. D. Kosambi describes some scientific aspects of numismatics. Coins also have a variety of simple properties that can be exploited in recreational mathematics: they stack easily, they can be used as counters, they can serve as models for points on the plane, they are circular and they have two distinguishable sides. Here is a collection of entertaining coin puzzles that require no more than 10 pennies. They are elementary enough to make excellent bar or dinner-table diversions, yet some of them lead into areas of mathematics that are far from trivial.

One of the oldest and best coin puzzles calls for placing eight pennies in a row on the table [*see upper illustration below*] and trying to transform them, in four moves, into four stacks of two coins each. There is one proviso: on each move a single penny must "jump" exactly two pennies (in either direction) and land on the next single penny. The two jumped pennies may be two single coins side by side or a stacked pair. Eight is the smallest number of pennies that can be paired in this manner. The reader will find it a pleasant and easy task to solve the problem, but now comes the amusing part. Suppose two more coins are added to make a row of 10? Can the 10 be doubled in five moves? Many people, after finding a solution for eight, will give up in despair when presented with 10 and refuse to work on the problem. Yet it can be solved instantly if one has the right insight. Indeed, as will be explained in this department next month, a solution for eight makes trivial the generalization to a row of $2n$ pennies ($n > 3$), to be doubled in n moves.

The doubling problem

When pennies are closely packed on the plane, their centers mark the points of a triangular lattice, a fact that underlies scores of coin puzzles of many different types. For example, start with six pennies closely packed in a rhombus formation [*at left in lower illustration below*]. In three moves try to form a circular pattern [*at right in illustration*] so that if a seventh coin were placed in the center, the six pennies would be closely packed around it. On each move a single coin must be slid to a new position so as to touch two other coins that rigidly determine its new position. Like the doubling puzzle, this too has an amusing angle when you show it to someone. If he fails to solve it, demonstrate the solution slowly (it will be given next month) and challenge him to repeat it. But when you put the coins back in their starting position, set them in the mirror-image form of the original rhombus. There is a good chance that he will not notice the difference, with the result that when he tries to duplicate your three moves, he will soon be in serious trouble.



A close-packing problem

A good follow-up to the preceding puzzle is to pack 10 pennies to form a triangle [*at left in top illustration on opposite page*]. This is the famous "tetractys" of the ancient Pythagoreans and today's familiar pattern for the 10 bowling pins. The problem is to turn this triangle upside down [*at right*] by sliding one penny at a time, as before, to a new position in which it touches two other pennies. What is the minimum number of required moves? Most people solve the problem quickly in four moves, but it can be done in three. The problem has an interesting generalization. A triangle of three pennies obviously can be inverted by moving one coin and a triangle of six pennies by moving two. Since the 10-coin triangle calls for a shift of three, can the next largest equilateral triangle, 15 pennies arranged like the 15 balls at the start of a billiard game, be inverted by moving four pennies? No, it requires five. Nevertheless, there is a remarkably simple way to calculate the minimum number of coins that must be shifted, given the number of pennies in the triangle. Can the reader discover it?

The tetractys also lends itself to a delightful puzzle of the peg-solitaire type. Peg solitaire, traditionally played on a square lattice, is an old recreation that is now the topic of a considerable literature (see "Mathematical Games" for June, 1962). As far as I know, similar problems based on the triangular lattice have received only the most superficial attention. The simplest starting position that is not trivial is the Pythagorean 10-spot triangle. To make it easy to record solutions, draw 10 spots on a sheet of paper, spacing them so that when pennies are placed on the spots, there will be some space between them, and number the positions [*see bottom illustration on opposite page*].

The problem: Remove one penny to make a "hole," then reduce the coins to a single penny by jumping. The jumps

Triangle-inversion problem

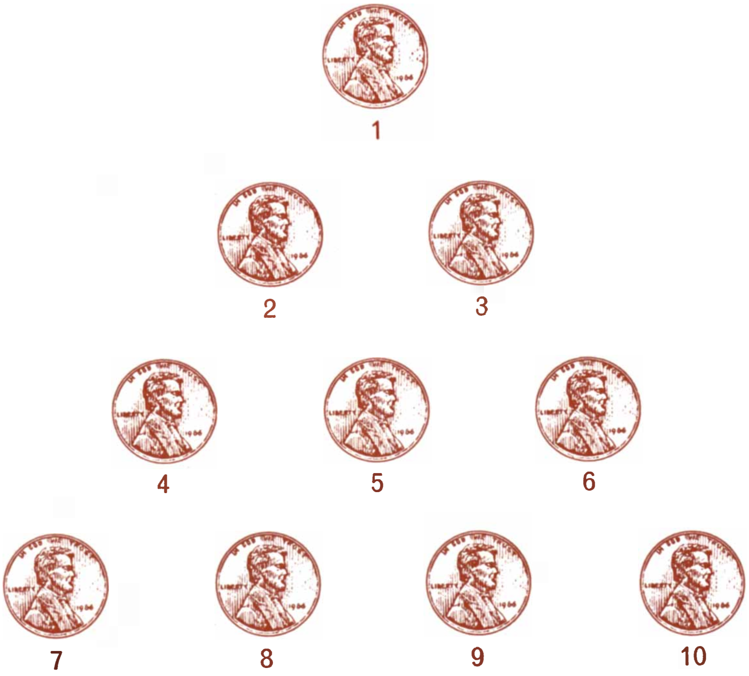
are as in checkers, over an adjacent coin to an empty spot immediately beyond. The jumped coin is removed. Note that jumps can be made in six directions: in either direction parallel with the base, and in either direction parallel with each of the triangle's other two sides. As in checkers, a continuous chain of jumps counts as one "move." After some trial-and-error tests one discovers that the puzzle is indeed solvable, but of course the recreational mathematician is not happy until he solves it in a minimum number of moves. Here, for example, is a solution in six moves after removal of the coin on spot 2:

1. 7–2
2. 9–7
3. 1–4
4. 7–2
5. 6–4, 4–1, 1–6
6. 10–3

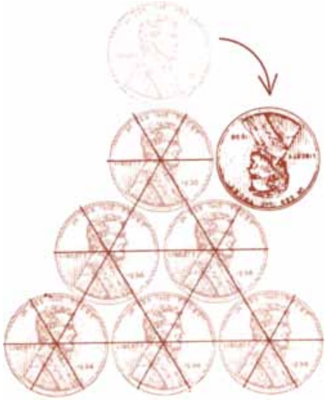
There is, however, a better solution in five moves. Can the reader find it? If so, he may wish to go on to the 15-spot triangle. The novelty company S. S. Adams has been selling a peg version of this for years under the trade name Ke Puzzle Game, but no solutions are provided with the puzzle and I do not know the minimum answer. Two 11-move solutions are given in Maxey Brooke's collection of coin puzzles, *Fun for the Money*. Are there better ones? Although I cannot reply to all letters, I shall report if any readers solve the 15-spot triangle in fewer than 11 moves.

If one penny rolls around another penny without slipping, how many times will it rotate in making one revolution? One might guess the answer to be one, since the moving penny rolls along an edge equal to its own circumference, but a quick experiment shows that the answer is two; apparently the complete revolution of the moving penny adds an extra rotation. Suppose we roll the penny, without slipping, from the top of a six-penny triangle [*see illustration at top left on next page*] all the way around the sides and back to the starting position. How many times will it rotate? It is easy to see from the picture that the penny rolls along arcs with a total distance (expressed in fractions of full circles) of 12/6, or two full circles. Therefore it must rotate at least twice. Because it makes a complete revolution, shall we add one more rotation and say it rotates three times? No, a test discloses that it makes four rotations! The truth is that for every degree of arc along which it rolls it rotates two degrees. We must double the length of the path along which it rolls to get the correct answer: four rotations. With this in mind it is easy to solve other puzzles of this type, which are often found in puzzle books. Simply calculate the length of the path in degrees, multiply by two and you have the number of degrees of rotation.

All of this is fairly trivial, but there is a beautiful theorem lurking here that has not been noticed before to my knowledge. Instead of close-packing the coins around which a coin is rolled, join them to form an irregular closed chain; the illustration at top right on the next page shows a random chain of nine pennies. (The only proviso is that as a penny rolls around it without slipping, the rolling coin must touch every coin in the chain.) It turns out, surprisingly, that regardless of the shape of a chain of a given length, the number of rotations made by the rolling penny by the time it returns to its starting position is always the same! In the nine-penny case the penny makes exactly five rotations. If the penny is rolled *inside* the chain, it will make exactly one rotation. This is also a constant, unaffected by the shape of the chain. Can the reader prove (only the most elementary geometry need be used) that for any closed chain of n pennies ($n > 2$) the number of rotations of the moving penny, as it rolls once around the outside of the chain, is constant? If so, he will see immediately how to apply the same proof to a penny rolling inside a chain of n coins ($n > 6$) as well as how to derive



Triangular solitaire



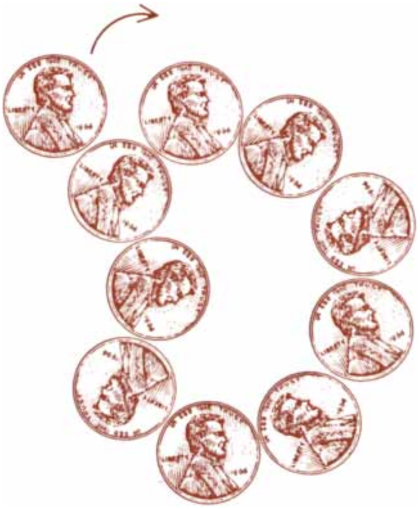
A rotation problem

a simple formula, for each case, that expresses the number of rotations as a function of *n*.

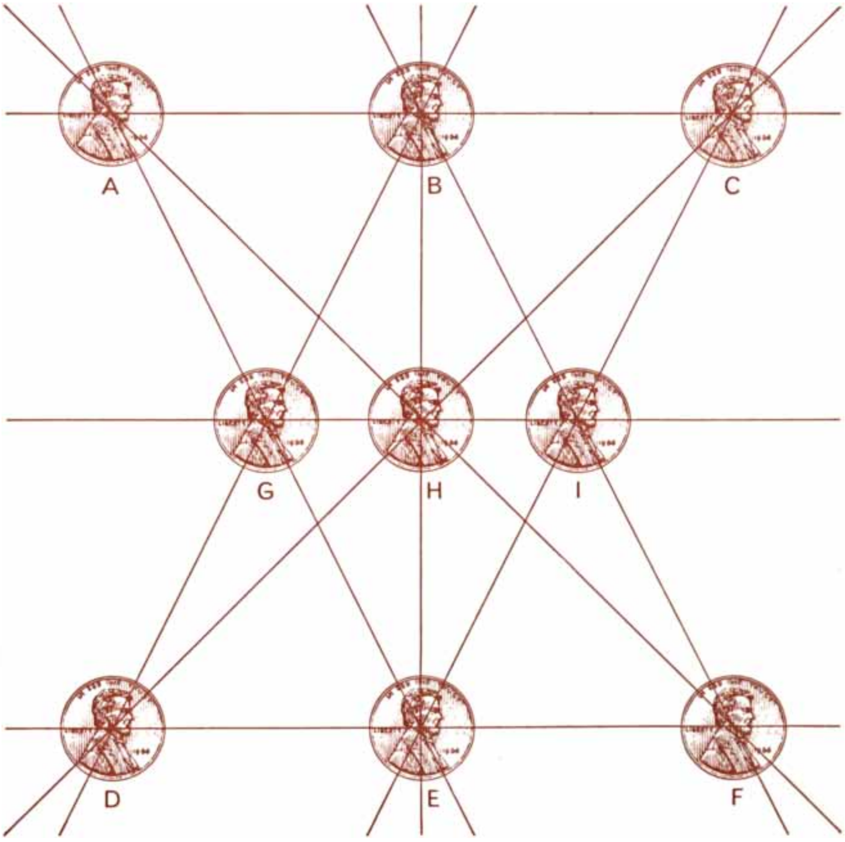
Pennies are also convenient markers for working on what in the puzzle field are called "tree-planting problems." For example, a farmer wishes to plant nine trees so that they form 10 straight rows with three trees in each row. If the reader is familiar with projective geometry, he may notice that the solution [*see bottom illustration on this page*] could be taken as a diagram for the famous theorem of Pappus: If three points *A, B, C* are located anywhere along one line, and three points *D, E, F* are located anywhere on a second line (the two lines need not be parallel as here), the intersections *G, H, I* of opposite sides of the crossed hexagon *AFBDCE* will be on a straight line. The Pappus theorem therefore guarantees nine three-point lines; the 10th line is added by adjusting the figure to bring points *B, H, E* into line. Tree-planting puzzles tie in with an aspect of projective geometry called "incidence geometry" (a point is incident to any line passing through it, and a line is incident to any point it passes through). Harold L. Dorwart of Trinity College has just published a splendid popular introduction to this subject, *The Geometry of Incidence* (Prentice-Hall), which I recommend to readers of this department. On page 146 he cites two tree-planting problems —25 trees in 10 rows of six to a row and 19 trees in nine rows of five to a row—both of which are solved by inspecting the figure for the famous projective theorem of Desargues. Tree-planting problems lead into deep combinatorial waters. No one has yet discovered a general procedure by which all problems of this kind can be solved, and the field is therefore riddled with unanswered questions.

Now back to our pennies. It turns out that 10 of them can be arranged to form five straight lines, with four in each line. (It is assumed, of course, that each line must pass through the centers of the four coins on it.) The illustration on page 116 shows five ways it can be done. Each pattern can be distorted in an infinity of ways without changing its topological structure; they are shown here in forms given by the English puzzlist Henry Ernest Dudeney to display bilateral symmetry for all of them. There is a sixth solution, topologically distinct from the other five. Can the reader discover it?

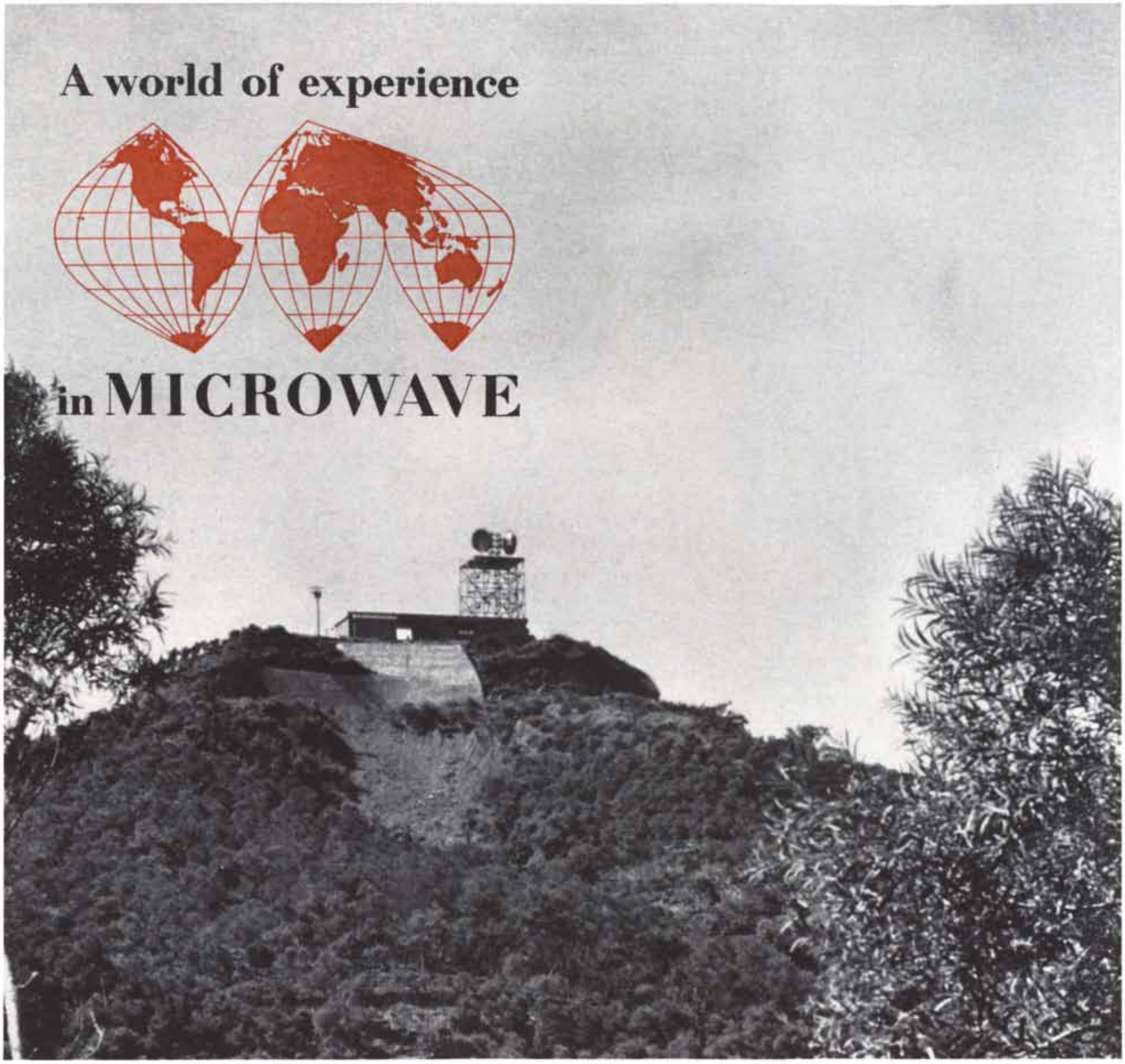
Many coin puzzles combine a bit of mathematics with "catch" features that make them excellent quickies of the "bar bet" type. For example, arrange four pennies in a square formation on the bar and bet someone you can change the position of only one penny and produce two straight rows with three pennies in each row. It looks impossible, but the solution is to pick up a penny and put it on *top* of the penny diagonally opposite. Here are two more penny catches: First, arrange three pennies as shown in the top illustration on page 118 and challenge someone to put penny *C* between *A* and *B* so that the three coins lie in a straight line—without moving *B* in any way, without touching *A* with his hands, with any part of his body or with any object and without moving *A* by blowing on it. For yet another bet, draw a vertical line on a sheet of paper. The challenge is to position three pennies in such a way that the surfaces of two heads are whol-



A surprising invariance theorem



Tree-planting problem and Pappus' theorem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13

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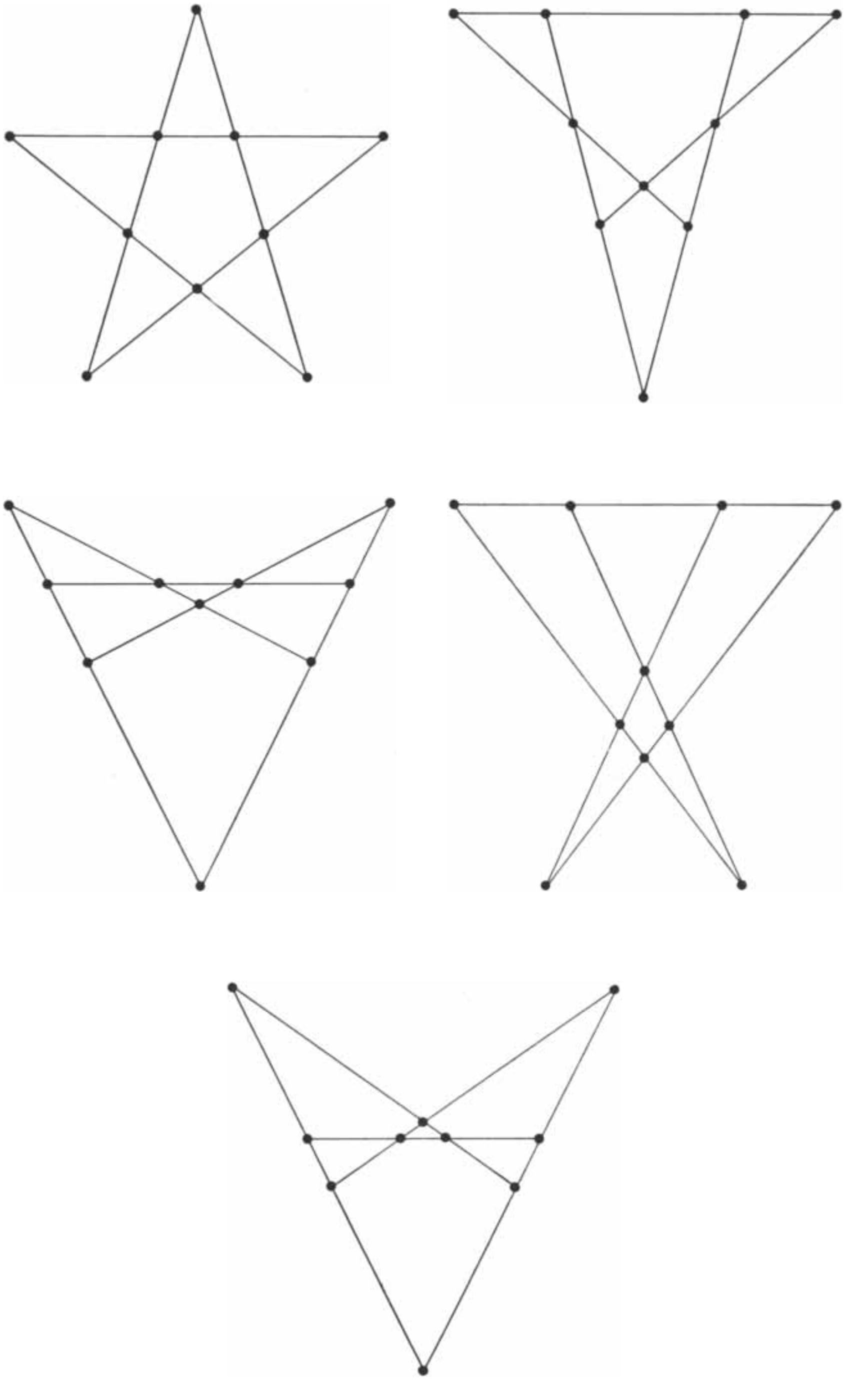
ly to the right of the line and the surfaces of two tails are wholly to the left of the line. Both bar bets, and all preceding problems, will be answered next month.

The first of last month's numerology problems was to explain the curious number 32650494425, which appears on page 331 of *The Scientist Speculates: An Anthology of Partly-Baked Ideas,* edited by I. J. Good. What could be a simpler way to half-bake a pi than to add the 10 digits, in the order shown, to pi's first 10 decimals:

$$\begin{array}{r} 3.1415926535 \\ .1234567890 \\ \hline 3.2650494425\,. \end{array}$$

The two numbers formed by the 10 digits that have the largest product are 96,420 and 87,531. Among pairs of numbers that have the same sum the pair with the largest product is the pair most nearly equal. This rule leads us



Five ways to plant 10 trees in five rows of four each

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to solve the problem by taking the digits in descending order, starting two numbers with 9 and 8, then annexing the remaining digits by pairs, the larger of each pair always joining the smaller of the two numbers: 9 and 8, 96 and 87, 964 and 875, and so on.

The number 8549176320, produced by the indexer named Betty, is simply the 10 digits in alphabetical order. (Note also that the letters in "Betty" are alphabetized.)

Harry Hazard's cryptarithm multiplication problem

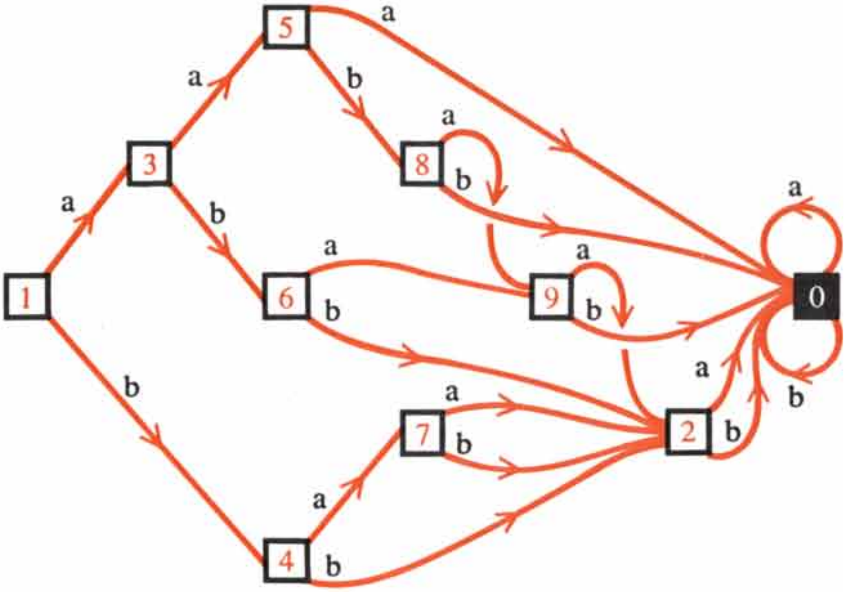
LYNDON
B
JOHNSON

has the unique answer

570140
6
3420840 .

Letters received concerning the short problems of last November contained many surprises. A number of readers solved the problem of finding formulas for the smallest number of unit lines that must be removed to "kill" all squares in a square matrix of odd or even order. George Brewster, John W. Harris and Andrew Ungar were the first U.S. readers and D. J. Allen and John Dickson were the first British readers to draw a single diagram that could be extended to display all solutions rather than separate diagrams for the odd and even cases. Many readers, attacking the companion problem of creating "rectangle-free" patterns, pointed out that the *L*-tromino plays in this problem the same role the domino plays in the square-free problem. Harris achieved the lowest records, using a procedure that can be continued to all higher orders: three unit lines for the order-two square, seven for order-three, 11 for order-four, 18 for order-five, 25 for order-six, 34 for order-seven and 43 for order-eight. His order-eight pattern is shown at the bottom of the next page.

Stephen Barr's problem of finding three sets of cocircular points in a picture of randomly dropped rectangles and disks proved to be better than he realized. J. K. Baillie, Richard A. Brouse, David E. Casteel, Larry Fisher, G. R. Gamertsfelder, Robert E. Hurley, Joseph C. Hyl, Thom Sulanke and Robert L. West were the first to call attention to a *fourth* set of cocircular points. Referring to the diagram given in December, the four points are *A*, the unmarked intersection immediately below *A* on the right, *B* and the unmarked



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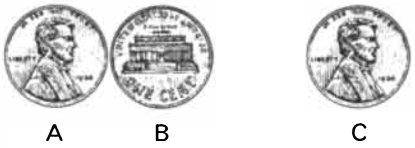
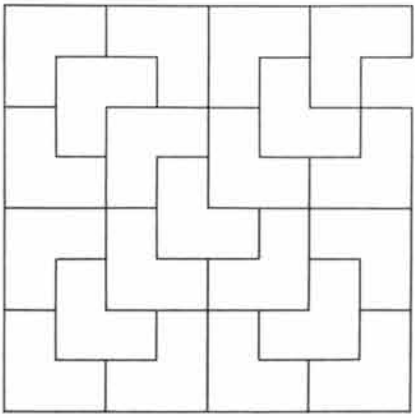


A three-penny bar bet

corner just above *B*. A line joining *B* and the point below *A* is the diameter of a circle on which the other two points lie, since each is the vertex of a right angle subtending the diameter.

John A. Fotheringham, David B. Hall, Glenn M. Roe, John S. Steadman, Phillip Stein, James E. Stuart and Sylvia Young were the first to defend the police commissioner in the problem about testing for the poison glass. Regardless of the number of glasses, the most efficient testing procedure is to divide them as nearly in half as possible at each step and test the glasses in either set. When the probabilities are worked out, the expected number of tests of 129 glasses, if the halving procedure is followed, is 7.0155+. But if a single glass is tested first, the expected number is 7.9457+. This is a rise of .930+ test, so the commissioner was almost right in considering the mathematician's procedure a waste of one test. Only if there had been 129 glasses, however, do we have a plausible excuse for the error, so, in a way, the problem was correctly answered even by those readers who proved that the mathematician's test procedure was inefficient.

Many readers wrote to say that STY, *sty*, would not be the last common word to appear in the anagram dictionary that was the subject of the first problem last November. It would be followed by SU, *us*.



Rectangle-killing on the order-eight lattice

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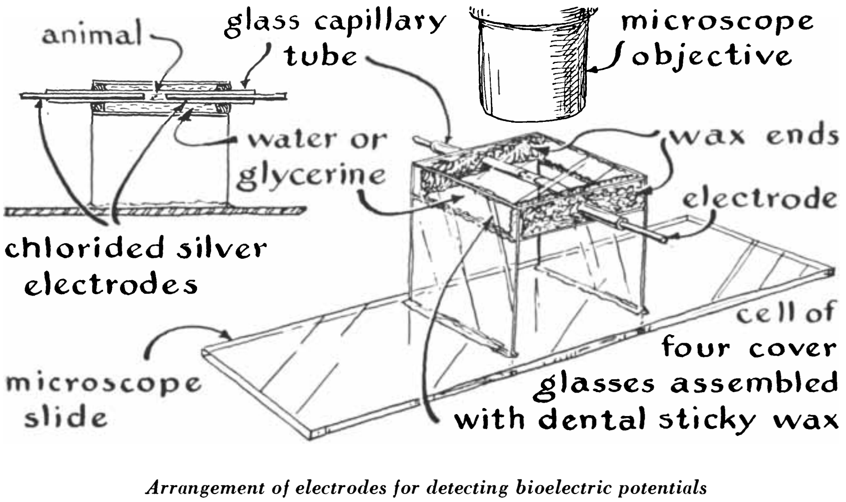
How to record and listen to the electrical signals produced by microscopic animals

Conducted by C. L. Stong

Small animals such as the so-called water flea are unusually engrossing when they are heard as well as seen. This is evident if one puts an animal of this size on the stage of a low-power microscope and connects the animal to a loudspeaker—a task less difficult than it sounds. Any animal can actuate a sensitive amplifier and loudspeaker because the electrical discharge that accompanies the functioning of animal cells is common to animals of all sizes. Richard F. Wheeler, a student at Foothill Junior College in Los Altos, Calif., has assembled the appropriate apparatus and has conducted experiments in amplifying the sounds made by very small animals. He has worked particularly with *Daphnia,* which is commonly called a water flea but is actually a tiny crustacean. He has also made simultaneous sight-and-sound observations of *Cyclops* (another genus of water flea), mosquito larvae and such microscopic animals as rotifers, paramecia, vorticellae and ostracods.

The cell of an animal has been likened to a simple insulated container of electrons, or negative charges. Positive ions in the surrounding fluid are attracted by the electrons to the external surface of the insulating membrane. Hence an electrostatic field, or potential difference, exists across the membrane. When the cell is in the resting state, the membrane exhibits good insulating properties: it is quite impermeable to all ions. External forces, either electrical or chemical, can lower the resistance of the membrane, however, with the result that both electrons and ions migrate through the wall and combine. The movement of such charges constitutes an electric current that sets up a potential difference throughout the fluid in the cell and its environment. A discharge of one cell can trigger the discharge of its neighbors and so initiate a current pulse of substantial magnitude. The resulting pulse of voltage can be detected by appropriate electrodes, such as a pair of silver wires, placed anywhere in the fluid.

Following the discharge, the membrane recovers its insulating property and metabolic processes restore the initial charged condition to the cell in preparation for the next cycle. The entire interval of discharge and recovery may be no more than a few thousandths of a second. Although the energy liberated by even a large group of cells is small with respect to that flowing from a flashlight battery, it is more than enough to operate a loudspeaker system of the kind used for reproducing phonograph recordings. In making electrocardiograms of water fleas, Wheeler has measured potentials of 20 to 600 millionths of a volt across silver electrodes placed near a *Daphnia.* This is a substantial "signal" in terms of modern electronics.



Arrangement of electrodes for detecting bioelectric potentials

In many cases sight alone will be insufficient for observing the activities of such small animals. For example, the observer watching a specimen of *Daphnia* under a microscope will see water streaming along one side of the animal at fairly high velocity. The cause of the motion is not easy to detect by eye unless the animal has been killed and stained; it then becomes evident that the motion must arise in limblike structures adjacent to the midventral section. Such a specimen, however, is obviously incapable of movement. This is where the loudspeaker becomes valuable. You can learn what is going on as you watch a living specimen of *Daphnia,* or one of the other animals, and listen to it at the same time. If you include in the experimental setup a stroboscopic ("strobe") lamp, a photocell, a camera, a pen recorder, a magnetic-tape recorder and an oscilloscope, you will be able to obtain a detailed account of the water flea's behavior.

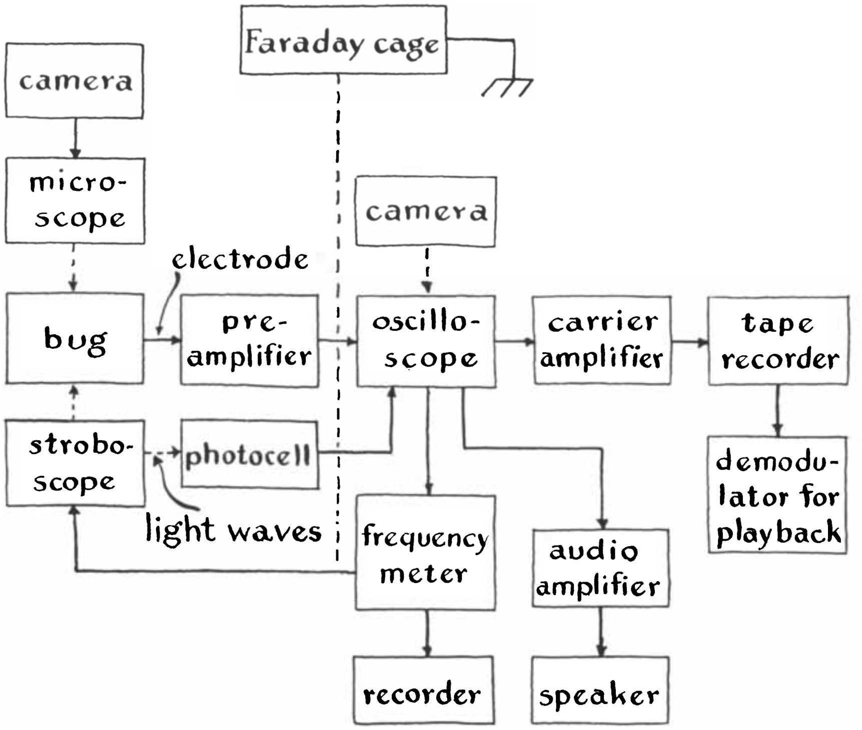
Wheeler writes that his interest in recording bioelectric potentials from small animals began with an article in this department (January, 1962). He continues: "The author dealt mainly with the technical problems of picking up potentials from large animals such as fishes and did not dwell on the development of the miniature electrodes that must be used for connecting an amplifying apparatus to animals of microscopic size. The article raised three questions in my mind. If bioelectric potentials can be successfully detected and recorded from small crustaceans such as those discussed in the article, can they also be detected and recorded from protozoans? If the potentials from protozoans can be recorded, can the records be used for investigating ciliary movement? Finally, does the presence of systematically controlled currents in protozoans suggest the existence of a nervous system on the molecular level?

"For apparatus I bought some instruments, borrowed others and made the rest. I built a Faraday cage: a box lined with copper screening that could be connected by wire to a water pipe for shielding the recording electrodes from electrical interference. During the course of the experiments the box turned out to be too small for the equipment, so I borrowed a larger one from the physiology department of Stanford University.

"The lamp used for lighting the stage of the microscope operated on alternating current that interfered with the signal from the specimens. To eliminate this source of noise I constructed a direct-current power supply for the lamp. Perhaps the most useful piece of accessory equipment was a special amplifier that powered the loudspeaker. This unit enabled me to follow the electrical signals by ear while observing the movements of the animal and so eliminated the necessity of shifting my eyes alternately from the specimen to the pen recorder.

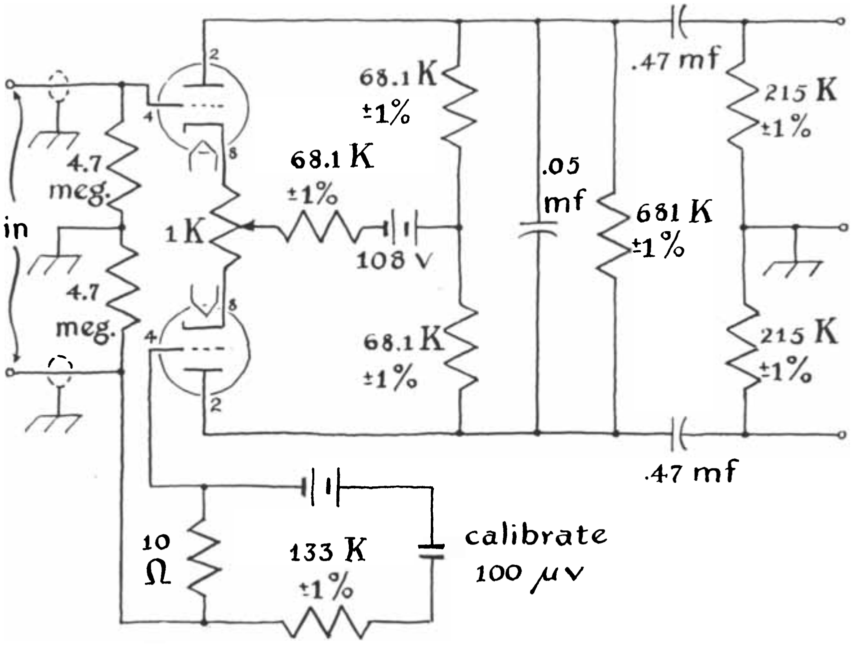
"Most of my time and effort during the construction phase of the experiment went into the development of suitable microelectrodes. None of the available electrode systems that are normally used for picking up bioelectric potentials from gross tissue was adequate; therefore I had to improvise my own. The first arrangement consisted of four needles from an electroencephalograph. I paired them, spaced the two needles of each pair about three millimeters apart and inserted the pairs on opposite sides of a piece of three-millimeter, clear-plastic tubing that was closed at one end. I hoped to trap the animal inside the tubing, between the tips of the needles.

"The arrangement did not prove satisfactory because of difficulty in making a good mechanical attachment to the needles. Moreover, an air bubble was invariably trapped in the closed end of the tube. Subsequent changes in temperature caused the trapped air to expand and contract, with the result that the drop of water containing the specimen migrated slowly beyond the needles that were intended to serve as electrodes.

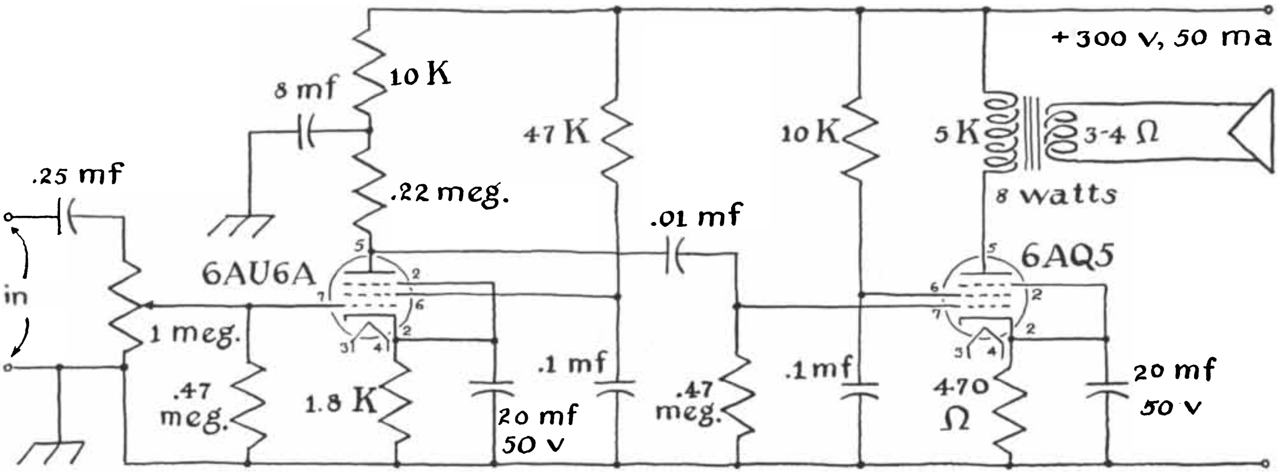


Equipment inside (left) *and outside* (right) *shielded box*

"Several arrangements that involved placing metallic foil in open containers were then tried. In one system a five-milliliter beaker was lined with four equal rectangles of aluminum foil. A fifth sheet of foil was placed on the bottom of the container and a sixth sheet, supported above, made contact with the upper surface of the fluid. The arrangement was intended to localize potentials in three dimensions from larger animals such as tropical fishes, mosquito larvae and water boatmen. The scheme worked rather well with large specimens and merits further development. On the other hand, it is quite sensitive to vibration, which appears as noise in the electrical system. The system is much too large for *Daph-*



Circuitry of the preamplifier



Circuitry of the audio amplifier

nia and similar small specimens in which I am primarily interested.

"Other electrode schemes consisted of suspending a drop of water containing the specimen between the ends of two needles or between small holes in two closely spaced sheets of tinfoil. The drop suspended between the needles by surface attraction evaporates too rapidly for practical use. It is also relatively insensitive and difficult to assemble. The drop suspended between sheets of tinfoil is a sensitive electrical pickup and can be lighted from below for microscopic observation, but the curvature of the upper surface of the water acts as a convex lens that grossly distorts the image. The distortion can be prevented by placing thin sheets of glass, such as microscope cover slips, in contact with the upper and lower surfaces of the drop and cementing the glass to the foil with sealing wax that has a low melting point, such as the sticky wax used by dentists. This structure is somewhat difficult to put together, but it works.

"Various arrangements were also tried that involved placing conducting wires and foils at the sides of microscope slides and cover slips. Most were insensitive because of the large separation of the electrodes. Electrodes in the form of foil strips cemented to the microscope slide proved to be sensitive to vibration and hence acted as generators of noise.

"The most successful and generally useful electrodes finally devised consist of silver wires thrust into the ends of a glass capillary tube with a bore about two millimeters in diameter. The tube is supported in water in a glass cell made of cover slips. The assembly is mounted on a microscope slide. The glass cell, capillary tube and slide are attached with sticky wax [*see illustration on page 120*].

"The specimen occupies the space between the ends of the wires inside the capillary. To improve the chemical stability of the electrodes the inner ends of the silver wires are cleaned, connected to a 1½-volt dry-cell battery and immersed for about 15 minutes in a solution of approximately one part of hydrochloric acid to 25 parts of distilled water. The polarity of the electrodes is then reversed and, with the wires still immersed in the dilute acid, the current is applied for another 15 minutes. Incidentally, cover slips can be broken into particular shapes and dimensions easily if they are first scored lightly with a diamond point.

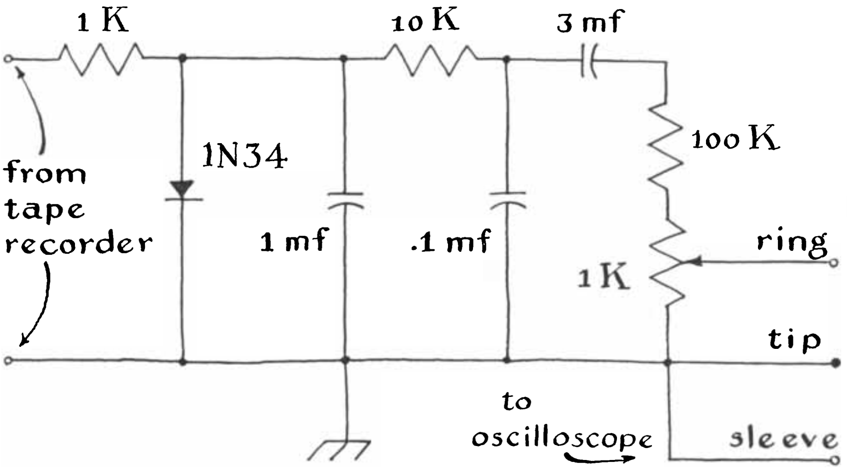
"In air the capillary tube acts as a cylindrical lens that distorts the image of the specimen. The distortion can be minimized by filling both the tube and its surrounding cell with water; this is successful in spite of the fact that the refractive index of water is substantially lower than that of glass. A better optical match could be achieved by filling the cell with a solution, such as glycerol, that has a refractive index approaching that of glass. Care should be taken, however, to avoid contaminating the water inside the tube with glycerol and so damaging the specimen. All specimens are normally observed in distilled water.

"Electrodes of this type for use with protozoans must be made smaller, both to prevent the animals from swimming out of the space between the ends of the wires and to reduce the spacing between the electrodes, thus improving the sensitivity. I first select silver wire of the desired size. The material can be bought from jewelry manufacturers.

"The wire is placed in a convenient length of capillary tubing, which is then heated to a soft state in the flame of a gas burner. The tube is promptly stretched so that the bore shrinks to the diameter of the wire over a length of about two centimeters. After cooling, the glass is immersed in a bath of nitric acid until the metal is etched away. The glass tube is then fitted with wire electrodes. The completed electrode assembly can be attached to a micromanipulator for observation under a low-power stereoscopic microscope or placed on the stage of a conventional high-power microscope. I connect the silver electrodes to a coaxial cable that transmits the input signal to a preamplifier. The outer conductor of the cable is grounded to the wire screening of the Faraday cage.

"Although this electrode configuration has resulted in a number of satisfactory recordings, I am still trying to improve it. At present, for example, I am placing thin-film gold electrodes on microscope slides by evaporating the metal in a vacuum. This arrangement has developed exceptionally strong signals. I also plan to use half-silvered slides. With the animal between two transparent but electrically conducting slides the whole problem of simultaneously achieving large surface area and good visibility may be solved.

"The opportunity to experiment with the thin-film packages intended for use as integrated circuits is also tempting. Some of these devices have as many as 10 miniature electrodes that terminate in an area of only a few square millimeters [see "Microelectronics," by William C. Hittinger and Morgan Sparks; SCIENTIFIC AMERICAN, Novem-



Wiring of the carrier demodulator

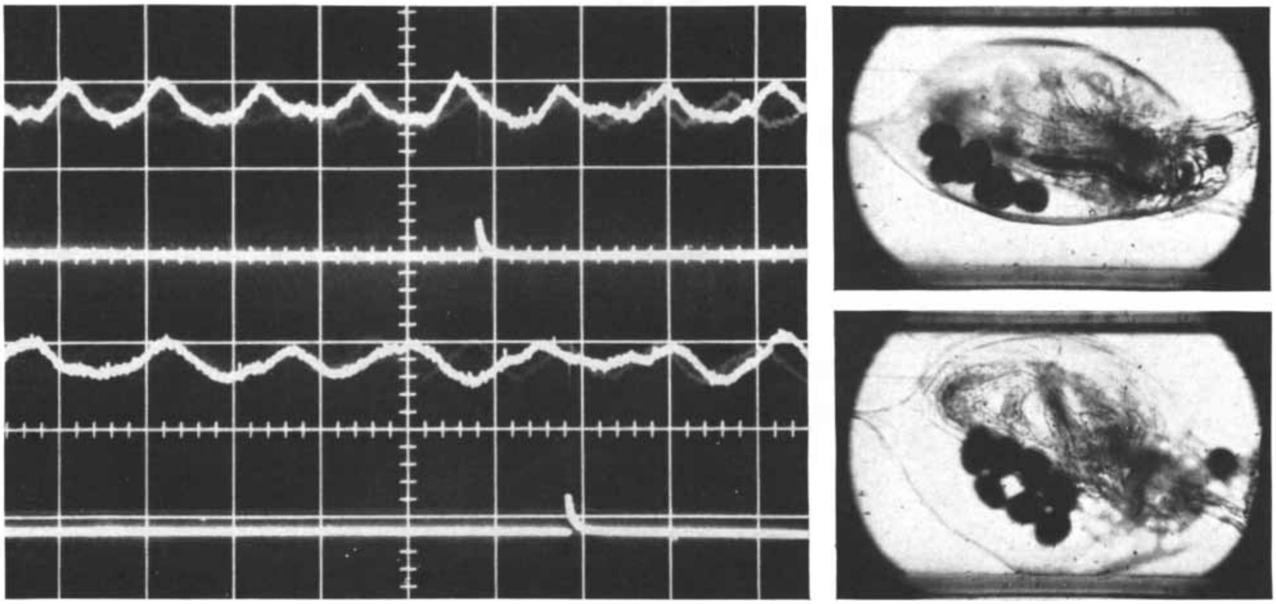
ber, 1965]. This area could be flooded with solution and sealed with a cover slip. Rejects are fairly easy to procure. Unwanted circuits can be etched off the assemblies with the combination of concentrated nitric and hydrofluoric acid that is designated by the code number CP-8.

"In general the instruments used for amplifying and displaying the signal operate in two groups. The group inside the shielded box includes the specimen cell, microscope, camera, strobe lamp, photocell and preamplifier. The unshielded group consists of the oscilloscope and an associated camera for photographing the display; a frequency meter, a pen recorder, a loudspeaker and an associated audio amplifier; a carrier amplifier that feeds a 400-cycle current modulated by the signal to a magnetic tape recorder, and a demodulator for recovering the signal. The carrier is necessary because my tape recorder does not respond to frequencies as low as those of the signal.

"The eyepiece of the microscope is accessible for viewing the specimen without opening the shielded box. When the strobe lamp is flashed for making a photomicrograph of the specimen, the photocell picks up the light and transmits a voltage pulse to the oscilloscope and the recorders. The pulse appears as a timing mark on all displays and correlates the position of all visible parts of the specimen with the electrical potentials present at the instant the picture is made.

"It is rather easier, I find, to gather the data than to interpret it. I have recorded and definitely identified electrocardiograms of *Daphnia* [*see top illustration on next page*]. The graph of individual beats is roughly similar in shape to the discharge of a single cell. The large pulse on the left side of the record may have been caused by a twitch of the water flea's antennae, although I was not watching the animal when this feature appeared. The pulse rate of *Daphnia* is about 600 beats per minute. On the other hand, the animal's heart occasionally stops and then resumes beating. The reason for this is puzzling unless the pause serves as an interval of rest and recovery.

"Respiration is likewise interrupted from time to time. Its frequency varies in such a way as to suggest that something is acting as a feedback mechanism, but I have no idea what the mechanism could be. The accompanying illustrations [*below*] show respiration potentials at two intervals. The vertical lines on both graphs represent time intervals of .2 second per centimeter and the horizontal lines indicate signal potentials of 200 millionths of a volt per centimeter. The straight graphs below each contain a timing 'pip' that registers as an upward excursion of the pen at the instant the photomicrographs are made. The upper and lower pictures correspond respectively to the top and bottom graphs. The eye of this female specimen appears at the extreme right and the brood pouch, containing seven eggs, is at lower left. The faint, fuzzy object immediately to the right of the eggs is the heart. The respiration rate of



Views of Daphnia *coincident with respiration signals*

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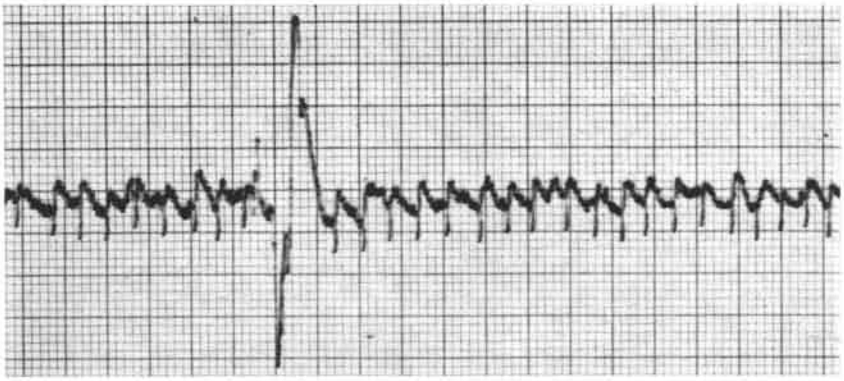
this specimen varied from a high of 270 per minute (as shown by the upper graph) to approximately 210 per minute (as shown by the second recording). The signal strength averages about 80 millionths of a volt in both.

"When respiration and pulse are suspended at the same time, it is possible to make a clear recording of *Daphnia's* antenna movements. Each movement occupies only about 20 thousandths of a second on the average [*see middle illustration below*]. Graphs of respiration and pulse that occur simultaneously are not particularly meaningful, but an example is included [*see bottom illustration below*].

"I have devoted far more time to the study of *Daphnia* than to other organisms, although recordings of several other animals have been made. The antenna movements of the water flea *Cyclops,* an organism responsible for transmitting worm infections to humans, generates action potentials that closely resemble those of *Daphnia* [*see top illustration on page 127*]. Ostracods, on the other hand, make recordings of action potentials that appear to be associated with muscle twitches [*see middle*



Electrocardiogram of a water flea

Signals associated with antenna movements of a water flea

Electrocardiogram of water flea superposed on respiration graph

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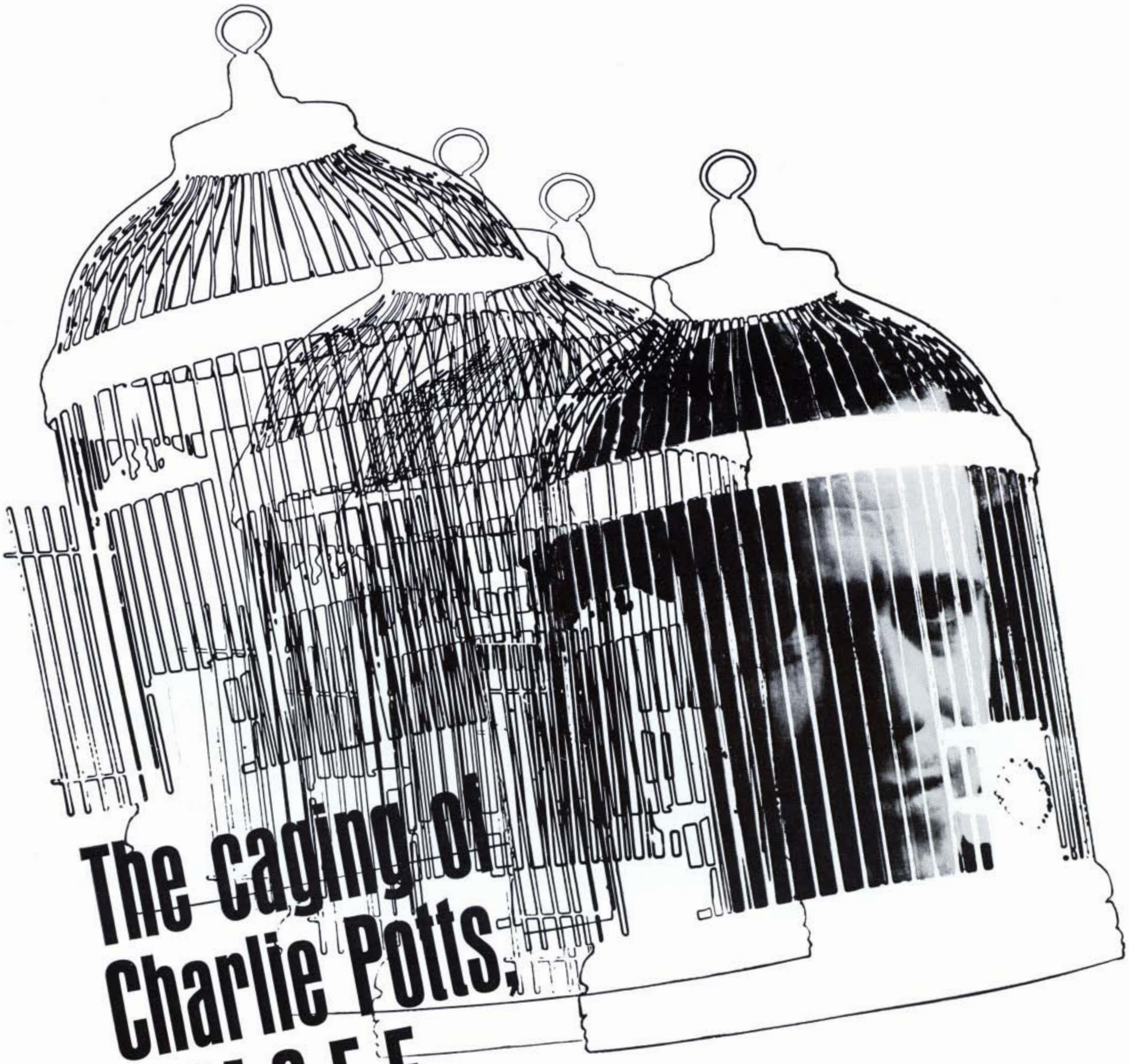

The caging of Charlie Potts, M.S.E.E.

Up and down, up and down, back and forth, back and forth, rest a minute, growl, back and forth, back and forth.

Charlie Potts was captured in 1958. The recruiters picked him right out of the top three percent of his class. He was talented, ambitious, bright, a real trophy.

Up and down, up and down.

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Back and forth, back and forth.

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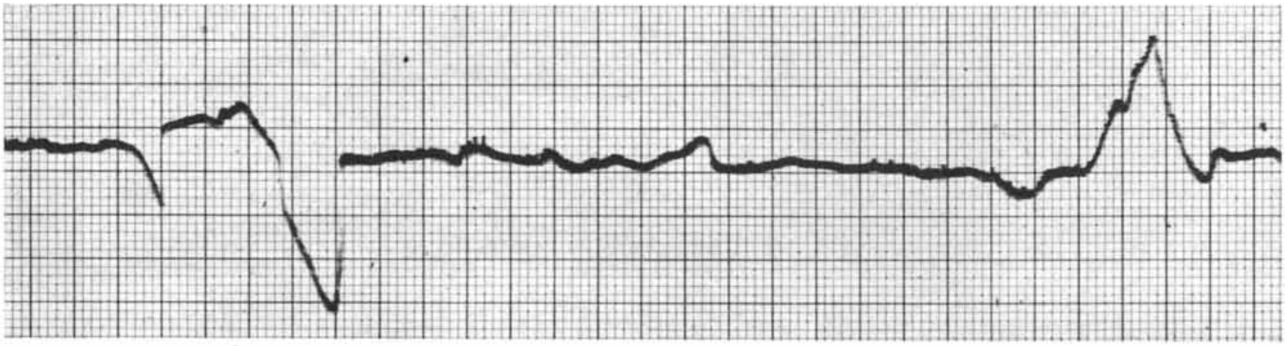
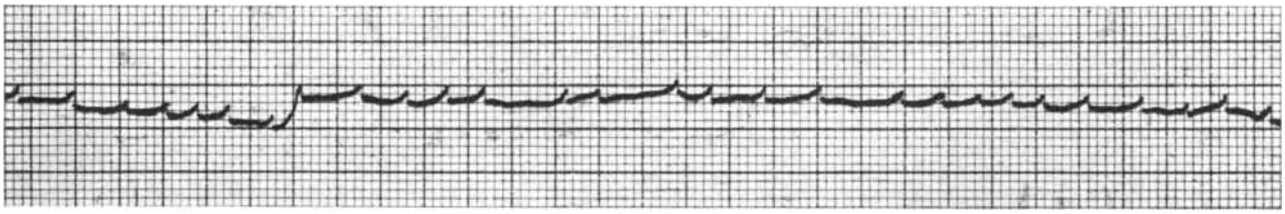
Signals associated with antenna movements of Cyclops



Spikes believed to represent muscle twitches of an ostracod



Electrocardiogram of mosquito larva

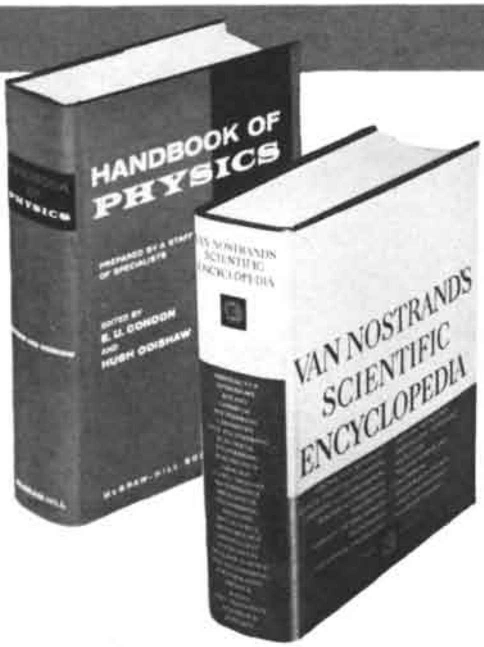
illustration above]. These organisms are enclosed by a pair of opaque shells that make it difficult to associate an action potential with the functioning of a specific organ.

"My electrocardiograms of mosquito larvae are cluttered somewhat by 'noise' generated by other muscle. These disturbances could doubtless be minimized by situating the animal with respect to the electrodes in a position that would emphasize its heart action. This would require more patience than I have yet summoned. Even so, the heartbeats are obvious on the graph and easy to count. The accompanying graph [*see bottom illustration above*] is relatively uncluttered by muscle noise. The pulse rate averages approximately 360 beats per minute.

"Although action potentials of several protozoans have been detected, I have not yet succeeded in making recordings worthy of publication. The technical difficulties of recording bioelectric potentials seem to vary inversely with the size of the animal. Potentials have been recorded from a paramecium when it collides with an object, stops and changes direction. The graph shows merely a spike, or pulse. An electrode assembly of greater sensitivity would doubtless deliver the continuous signal that according to theory must be present in the water.

"Impulses have also been detected from colonies of vorticellae. This animal resembles a minute, inverted bell equipped with a slender handle or stalk by which it is normally attached to bottom sediments. A muscle-like fibril spirals down the stalk. When the fibril is stimulated, it contracts violently, jerking the entire organism downward to the base of the stalk. The pulses I detected appear to be associated with these abrupt contractions, but my colony gave out before I could verify the effect, much less analyze it.

"In performing these experiments I have had a lot of help and encouragement from fellow members of our Amateur Research Center, Inc., a group of science enthusiasts some of whom live as far away as Berkeley and San Jose, a distance of about 60 miles. We have assembled a collection of instruments that are available to members on loan. In addition we hold regular seminars and publish a modest bulletin that reports our activities both as individuals and as a group. We plan to expand our facilities, and we hope to set up a program that will enable specially qualified amateurs to work at the center during summer months while holding part-time jobs that we would help to find in local industry. We welcome new members, even from across the country, and encourage the organization of similar groups everywhere. Our group is sponsored by the American Society of Safety Engineers. We shall be glad to correspond with anyone who would like to know more about our activity. Our address is: Amateur Research Center, Inc., Box 2337, Stanford University, Stanford, Calif. 94305."



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BOOKS

Are the principles of logical empiricism relevant to the actual work of science?

by Stephen Toulmin

Aspects of Scientific Explanation and Other Essays in the Philosophy of Science, by Carl G. Hempel. The Free Press ($12.50).

In his book *Consciousness and Society* the Harvard historian Stuart Hughes has mapped the decline of self-confident 19th-century positivism. Up until 1890 (it had seemed) the Newtonian program of physics and chemistry demanded completion by an equally "mechanomorphic" psychology and sociology, but from then on a new generation of men such as Sigmund Freud and Max Weber set about transforming psychological and social thought. For the first time scientists and philosophers were compelled to turn the mirror on themselves, and to acknowledge how deeply they were implicated in the very events about which they had hitherto claimed an "objective" knowledge. In this way was born that general concept of "the observer" which, in the hands of Albert Einstein and Werner Heisenberg, has similarly transformed the epistemology of physics.

Seen against this background (Hughes remarks), the rise of "logical empiricism" in the 1920's, with "the young philosophers-scientists of the Vienna Circle... taking up again—under the banner of intellectual liberation—positions that had apparently been definitively abandoned thirty years earlier," had a certain irony about it. Although the thinkers of the new school were happy to unload some of their grandfathers' "metaphysical rubbish," for example rejecting as superstition the belief in a natural necessity other than logical necessity, they revived the conviction that "scientific objectivity" was in principle an attainable ideal. The first step toward it, they believed, was "to fuse the methods of philosophy and mathematics and by so doing to bring greater rigor into the conceptual framework of both." The proper program for a scientific philosophy, including a philosophy of science, would be to concentrate on "those problems alone that could be formulated without ambiguity in logical or symbolic language." That was the general program that has been followed ever since, in different ways, by Rudolf Carnap, Hans Reichenbach, Carl G. Hempel and their disciples. Since most of the leading figures in the movement came to the U.S. in the 1930's, logical empiricism now represents a significant stream in American philosophy.

Forty years after its birth the movement that began in Vienna has had time to show results, and there could be no better opportunity for reappraising its achievements than that provided by the appearance of the new collection of Carl Hempel's essays. Hempel is as honest, as careful and as thorough an exponent of the method as one could ask. Moreover, he is, within the limits of his fundamental convictions, an entirely reasonable man who will go to painstaking lengths in the effort to meet the objections of his philosophical opponents and to reconcile them with his own points of view. Accordingly "Peter" Hempel, as he is familiarly known, is almost alone in the jungle of American academic philosophy as a man without enemies. It is a pleasure to salute him here, and to congratulate him on his many merits as a philosopher, notably on his patience, his tolerance and his awareness that monologue is not enough. Since he is a reasonable and tolerant man, he will be content if his views are treated with serious attention, and he will know better than to demand uncritical agreement. Therefore I feel free to raise here some fundamental doubts about the whole program with which he has been associated.

First of all, it is necessary to describe his new book. During the 20 years between 1940 and 1960 Hempel published nearly a dozen sizable papers, beginning with a much debated article entitled "The Function of General Laws in History" and culminating in "Studies in the Logic of Explanation," prepared in collaboration with Paul Oppenheim. In these papers he applied certain central theses about the logic of scientific argument to a variety of fields and topics, for example "ideal types" in sociology, "functional" analysis in anthropology and the classification of mental disorders. The first two-thirds (330 pages) of the new collection reprints the papers together with Hempel's own brief retrospective comments on them. The remaining 166 pages comprise the single comprehensive essay that gives its title to the book. This essay draws together into one systematic exposition all the main strands in Hempel's philosophy of science and his answers to the chief objections commonly made against his position. The title essay displays both a novel degree of technical polish in the presentation of Hempel's own theories and a certain added flexibility in dealing with the counterarguments. In general, however, his position emerges unaltered; except on points of detail it will not be necessary here to differentiate the middle-period Hempel of the 1940's and early 1950's from the vintage Hempel of the past 10 years.

About the more peripheral essays not much need be said. At their best, as in the comparison of "functional equivalence" in anthropology with "convergent adaptation" in organic evolution, they can be very illuminating. In their weaker moments, as in his discussion "Science and Human Values," the thought is somewhat diluted. But it is by his systematic philosophy of science that Hempel will wish to be judged, and that means judged by three things: (1) his "logic of confirmation," (2) his analysis of "explanation" and (3) his account of the "general laws" to which, in his view, all sound scientific explanations must appeal. These general laws, he insists—and this is the single most characteristic element in his entire philosophy of science—can have a genuine explanatory force only if they have the appropriate "logical form." As he puts it, they must have either "the universal conditional form $(x)(Fx \supset Gx)$ asserting that any instance of F is an instance of G" or "the basic statistical form . . . to the effect the statistical probability for an event of kind *F* to be also of kind *G* is *r*, or that $p(G,F) = r$ for short." A genuine explanation is then a demonstration that some such general law relates the phenomenon in question (the "explanandum"), either universally or with a determinate frequency, to the conditions of its occurrence.

Here it will be useful to clarify Hempel's conception of the role of logic in the appraisal of scientific reasoning. Like many contemporary logicians, he limits himself to criticizing the arguments by which scientific results are justified ex post facto. Although certain scientific methods and procedures may be more "reasonable"—even in some sense more "rational"—than others, scientific discoveries are "*psychologically guided and stimulated* by antecedent knowledge of specific facts . . . *not logically determined* by them." Hence the process of discovery is a matter for "methodology" or "pragmatics" and is not amenable to logical criticism. The "rules of inductive inference" apply only after a discovery is made, when a scientist seeks to validate his new insights for others, by presenting them as legitimate conclusions from his observational data. The challenge to the logician (as Hempel stated it in 1945) consists in the fact that "while criteria of valid deduction can be and have been supplied by formal logic, no satisfactory theory providing general criteria of confirmation and disconfirmation [for scientific hypotheses] appears to be available so far." His 20 years of effort have gone toward filling in this lacuna, which he has seen throughout as a defect within formal logic.

Yet one is immediately compelled to ask: How could this task ever have been merely a matter of improving our formal logic? The question of what kinds of argument carry weight in real-life natural sciences—and why—is extremely complex, and the relevance to those sciences of, say, the formalism of Russell and Whitehead's *Principia Mathematica* is something that needs to be demonstrated in specific detail, not taken for granted. That, however, is a necessity that Hempel, far from satisfying, seems barely to acknowledge. For instance, he speaks in his first essay about "the language of science" and we discover only from the small print in a footnote that this phrase refers, not to any actual mode of discourse to be found in *The Physical Review* or the *Journal of Experimental Biology*, but to "the lower functional calculus with individual constants . . . universal and existential quantifiers for individual variables, and the connective symbols of denial, conjunction, alternation, and implication."

Since Hempel does not provide in this book an adequate account of how his theory is supposed to apply to real science, we must try to construct an answer for ourselves. Evidently the analysis of "explanation" and the criteria of "validity" that form the heart of Hempel's philosophy are not meant to apply to the arguments of real-life scientists as they stand. At the very least those arguments must be recast in a "suitably formalized language that provides for quantificational notation," with "every extra-logical term . . . characterized either as primitive or as defined, each defined term possessing a unique definition in terms of primitives." With this qualification, however, Hempel was prepared in 1958 to declare emphatically that "the decisive requirement for every sound explanation remains that it subsume the explanandum under general laws." It is true that he seems to take back this declaration in a 1964 postscript, which (recalling his alternative, statistical mode of explanation) complains that "some commentators seem to attribute to me the view that all adequate scientific explanations must be . . . by deductive subsumption under laws." But it is clear from the new title essay that he still regards "universal conditionals" and "statistical frequencies" as between them exhausting the entire range of legitimate explanatory principles.

Alternatively, then, are Hempel's logical patterns intended as abstract idealizations? Pointing in this direction is one passage in the new essay, in which he concedes that "the construction of our models therefore involves some measure of abstraction and of logical schematization." If this is his intention, we are faced with a different problem: that of seeing how the proposed formal idealization can be set in analogy beside the actual record of argument preserved in the conceptual history of the real-life natural sciences. This is not a problem to be set aside. When Newton undertook to replace the earlier intuitive notions of effort (or impulse), bulk (or weight) and quantity of motion by the formalized concepts of force, mass and momentum, the burden of proof was on him to demonstrate, specifically and in detail, the intellectual profits to be gained by doing so. If logicians correspondingly wish to replace our working conceptions of "validity," "confirmation," "proof" and the like by formalized substitutes, the burden lies on them to demonstrate the exact bearing and advantages of this exchange.

Here also Hempel is silent. Anyone familiar with the actual sciences knows that there are crucial differences in form, function and implications between, say, Boyle's law, Mendel's laws, Newton's laws of motion and of gravitation, the laws of thermodynamics and Heisenberg's principle of uncertainty. A philosopher of science can surely be asked to do some justice to the true variety of the kinds of general explanation, modes of argument and levels of discourse in which all these different "laws" figure. Hempel's formal schematizations smooth out these differences without comment or apology. He introduces variety into his examples simply by switching between "all ravens are black" on page 12, "all storks are red-legged" on page 105 and "all robins' eggs are greenish-blue" on page 266. These are the kinds of sentences he calls "laws of nature"! When critics confront him with counterexamples from the actual history of scientific thought, his response is oddly cavalier. The Darwinian account of the origin of species, for example, could be matched against his formal models only by the unrealizable requirement that we know vastly more about the prehistoric course of events than we actually do know. Does this mean so much the worse for the Hempelian models? No, it means so much the worse for the Darwinian theory and for the "widespread tendency to overestimate" the capacity of Darwinism to "account for . . . the evolutionary sequence." Note that in refusing the term "explanation" to the theory of mutation and natural selection Hempel has in mind no shortcomings of a biological nature. All he objects to is the failure of paleontological reasoning to conform to his own a priori patterns.

Only at two points does Hempel come significantly close to admitting that his method requires a broader justification. These are both to be found in the 1958 essay called "The Theoretician's Dilemma: A Study in the Logic of Theory Construction." This 50-page discussion faces with considerable frankness a paradox into which Hempel's approach appears to lead him: the conclusion that, if the primary aim of science is "establishing predictive and explanatory connections among observables," then appeals to "hypothetical entities" are either unsound or unnecessary. (If these appeals do succeed in drawing our attention to "connections among observ-

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ables," we can thereafter dispense with them; if they fail to do so, we can do without them from the start!) In point of fact this paradox is a genuine consequence of interpreting along strict Hempelian lines all the "regularities" and "general connections" with which natural sciences are concerned. Hempel escapes from it only by allowing that, over and above his initial function ("to establish deductive connections between observation sentences"), "hypothetical entities" have certain additional "heuristic" or "extra-logical" functions. Yet he never quite brings himself to face the deeper truth, namely that the "dilemma" in question is not a dilemma for the theoretician at all—what scientist ever thought twice about it? It arises only for the logical empiricist himself, being created by his own insistence that all significant theoretical propositions must be of the forms $(x)(Fx \supset Gx)$ and $p(G,F) = r$. A healthier reaction to the dilemma might well have been to see it as a *reductio ad absurdum* of the formal models themselves.

In the course of this particular argument Hempel again has occasion to switch our attention from the "scientific theories" we encounter in real life to the kind of "axiomatized systems" that are to be found in formal logic. For once it occurs to him to refer us to some actual cases in which scientific arguments have been deliberately "axiomatized." Yet the only instance he cites of an attempt by a natural scientist to axiomatize his own science is the work in biological theory of J. H. Woodger of the University of London. No example could be more unfortunate for Hempel's purpose. Woodger's proposed axiomatization of genetics could have been—if his professional colleagues had taken serious notice of it—a major obstacle to progress in the science. Like a good logical empiricist, he interpreted theoretical statements in genetics as universal or statistical correlations between observable macroscopic characters in animal populations. Next he set about redefining the term "gene" as an "intervening variable" in the system of formal theorems linking such observable characters. In this way he played down almost entirely the cytological and biochemical theories from which genetics had so much to gain. Even heuristically axiomatization was in this case a handicap rather than a help.

What, then, are the logical empiricists setting out to achieve? The answer to that question, I suspect, lies somewhere back in the Vienna of the 1920's where the movement originated. This much, at any rate, should be clear by now: For all its mathematical costume, the fundamental motives of Hempel's analysis are philosophical rather than scientific. Yet what pattern of philosophical preoccupations emerges from his new book? Above all, I think, a certain Platonism, not in the open assertion of hidden entities as much as in the mathematization of scientific criticism. Hempel's program requires that at every point in scientific argument the living, context-dependent utterances of scientists be replaced by articulations of unambiguous sentences, permanently qualified by the explicit specification of time and place. Only such timeless "sentential facts and events," he declares, can significantly be "explained."

Science emerges from this treatment not as an intellectual activity having a life and momentum of its own and governed by regulative concepts (force, conservation, information and the like) that shape the very patterns of theory and explanation. It emerges, rather, as a bare logical skeleton whose articulation may be quasi-mathematical—and accordingly more "permanent"—but whose formalization is purchased at the price of abstraction from the actual intellectual enterprise we call natural science. Whereas a century ago a philosopher such as William Whewell could see the philosophy of the inductive sciences as being inescapably bound up with their conceptual history, the logical empiricists of the 20th century dream instead of a "logic of science" that can escape the clutch of history. In my view the dream is a vain one.

To what end is this Platonizing directed? Here I can rely only on guesswork. In several places Hempel insists on the necessity for "objectivity" in stating the criteria of "validity" in scientific argument, but the only hint of what the "subjectivity" against which he is fighting might be comes from occasional passing and scornful references to, for instance, "neovitalism." Surely there must be more to it. Perhaps Stuart Hughes is right. Perhaps, having purged 19th-century positivism of naïve mechanomorphism, the philosophers of the Vienna Circle remained as nostalgic as ever for the objective certainties of the Newtonian world view. It is (as Hughes implies) somewhat ironic that the philosophy of logical empiricism should have flourished beside the science of Einstein and Heisenberg, Karl Lorenz and Norbert Wiener. Within 20th-century natural science the intellectual momentum has all been toward a greater involvement of the "observer" and the "observed," toward a deeper awareness of science as an activity rather than a mere formalism. So the reorientation toward self-consciousness that was characteristic of European social thought between 1890 and 1930 has also done much to transform our natural science. This change is scarcely to Hempel's liking. Einstein and Wiener get two perfunctory allusions in his 500 pages; Heisenberg and Lorenz are not mentioned. Once the very principles of natural science begin to involve the context of observation, and hence the interactions of the scientist and his subject matter, the logical empiricist can no longer hope to build up, from the analysis of real-life science, the kind of eternal structure of articulated sentences to which the work of men such as Euclid and Newton had accustomed him. No alternative remains except for him to construct his axiomatic systems for their own sake, in scholastic isolation from the historical development of real-life natural science, and, when the gap between the two becomes too blatant to ignore, to blame the scientists for not formulating their explanations "according to the rigorous standards of modern logic."

The resulting technical virtuosity may fill the reader with astonishment, but it is the virtuosity of a medieval disputation. Its place is less in the real world of scientific inquiry, where the painful elaboration of more adequate concepts and theories resists formalization in such elementary terms, than in the mandarin world of Hermann Hesse's *Glasperlenspiel*. This is not to say that the Emperor wears no clothes at all. It is just that his costume is formal and hieratic, leaving him free to perform certain purely liturgical rituals but disabling him from participating in the more varied and historically developing activities of workaday science.

Short Reviews

THE EARLIER LETTERS OF JOHN STUART MILL, 1812–1848, edited by Francis E. Mineka. University of Toronto Press ($20). To all doting parents who, because their small son is a wizard at the "new" mathematics or wins the public-speaking medal at school, are convinced he is a genius, it might be well to show a copy of the first recorded letter of John Stuart Mill written to his friend and protector Jeremy Bentham on July 28, 1812, when Mill was two months past his sixth birthday. The letter reads: "My Dear Sir, Mr. Walker is a very intimate friend of mine, who lives at No. 31 in Berkeley Square. I have engaged him as he is soon coming here, first to go to your house, and get for me the 3.^{d} and 4.th volumes of Hooke's Roman history. But I am recapitulating the 1.st and 2.^{d} volumes, having finished them all except a few pages of the 2.^{d}. I will be glad if you will let him have the 3.^{d} and 4.th volumes. I am yours sincerely." When Mill finished reading Hooke, he wrote a learned essay of some 1,500 words on the history of Rome that, among other things, was adorned with critical footnotes addressed to such matters as the Greek spelling of certain names in Langhorne's *Plutarch*.

This letter begins an admirable collection edited by Francis E. Mineka and published by the University of Toronto Press as part of a projected edition of Mill's writings. The letters cover a 36-year period up to the appearance in 1848 of Mill's *Principles of Political Economy*, by which time he had become an eminent public figure and his correspondence had taken on more of a public character. There are short letters of no consequence and longer ones filled with not much more than chitchat—although Mill was not what one would call a chitchatty man. There are also long letters to friends and intimates of his youth and early manhood, including Thomas Carlyle, John Sterling, Gustave d'Eichthal, Auguste Comte, Alexis de Tocqueville and William Johnson Fox. These are of extraordinary interest for the light they throw on Mill's internal conflicts and intellectual struggles, the breadth of his grasp and thought, and for what they tell us about leading literary and political figures of his time.

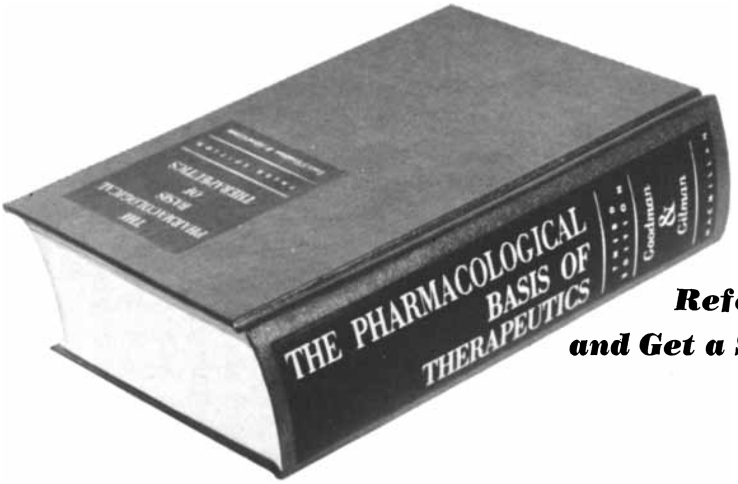
Mill is remembered as an economist, a philosopher and a social reformer. To these pursuits he made contributions of a high order; he was always passionately committed and brilliant. But reading these letters, together with his autobiography, one is equally struck by his essential goodness as a man and by his capacity in the midst of severe emotional difficulties to carry on his work—even to redouble his efforts. For Mill, as he once wrote Carlyle, the sovereign antidote to melancholy was to be able to do "something," to have, as he said, "a *choice* of work." This meant, for example, to write a treatise on logic as a form of happy leisure, away from "pettinesses," personal cares, politics and reform. In the House of Commons, Benjamin Disraeli once depicted Mill as "the finishing governess," and Mill's biographer St. John Packe said, not unjustly, that he had "the Victorian's passion for liberating the human mind from everything including sex." It is equally true, as the letters show, that Mill's magnificent intellect was ceaselessly applied to the task of enlightening understanding and bettering man's condition.

EXPERIMENTAL RESEARCHES IN ELECTRICITY, by Michael Faraday. Dover Publications, Inc. ($15). There is reprinted in these two volumes the three-volume edition of Faraday's *Experimental Researches* originally published between the years 1839 and 1855. This work is one of the masterpieces of scientific literature, setting forth with wonderful clarity and in explicit detail the step-by-step records of Faraday's investigations and discoveries, among them electromagnetic induction (which John Tyndall proclaimed as "the greatest experimental result ever obtained...the Mont Blanc of Faraday's own achievements"), the laws of electrolysis, the identities of different forms of electricity, the electrical capacities of various substances, the effect of magnetism on polarized light and diamagnetism. The books have been unaccountably out of print for a century and secondhand copies were not to be had except at an exorbitant price.

THE DAWN OF ASTRONOMY, by J. Norman Lockyer. The M.I.T. Press ($2.95). Norman Lockyer (1836–1920) was one of the major British astronomers of his time, a pioneer in solar and stellar spectroscopy and the inaugurator of the famous British journal *Nature*, which he edited from 1869 until his death. He was a man of many interests and idiosyncratic tendencies; for instance, after he had for some years been director of the solar physics laboratory at the Royal College of Science in London he suddenly left it and removed the instruments to his estate at Sidmouth, where he founded his own observatory. He turned his attention after 1890 to a problem that had also attracted Newton, the problem of bringing in astronomy to assist the chronology of history. In this connection he journeyed to Egypt to examine ancient monuments and in 1894 published a book, here reprinted in soft covers, that combines what Giorgio de Santillana describes as "fanciful speculations" about the origins of astronomy with "equally imaginative reconstructions of Egyptian history, ancient totemism, and the like." His primary aim was to show the astronomical character of Egyptian religion by means of architectural measurements and astronomical calculations and to demonstrate how these are represented in the "divine language" of inscriptions and literary texts. Egyptologists, archaeologists and philologists paid scant attention to his conclusions, and a later book of his on Stonehenge fared no better. Now, almost half a century after his death, interest in his views and his forgotten books has been reawakened by the work of Gerald S. Hawkins of Boston University. Hawkins, using an electronic computer to correlate his data, has reexamined the question of the chronology and design of Stonehenge. He has concluded that the monument was oriented to achieve certain astronomical alignments on the summer solstice and that Lockyer's inferences are "substantially correct for 1500 B.C." Thus the question remains open, and there is reason to believe that, in spite of the speculativeness of many of Lockyer's ideas, he may have been onto something real in certain of his opinions about the astronomical basis of the Egyptian and Celtic religions.

THE OXFORD COMPANION TO AMERICAN LITERATURE, by James D. Hart. Oxford University Press ($12.50). A revised and enlarged edition of this excellent companion for students and general readers that not only encompasses the leading authors of literature past and present, "popular and polite," but also treats major nonliterary aspects of the American mind and the American scene as these are reflected and influenced by American literature. For example, one finds such entries as the Museum of Modern Art, the Gastonia strike, Haverford College, the Roman Catholic Church in America, *The Springfield Republican*, the Hell-Fire Club and the Group Theatre as well as "The Secret Life of Walter Mitty," Eudora Welty, James Abram Garfield, Erle Stanley Gardner, *Scribner's Monthly*, *The Member of the Wedding*, Ernest Hemingway and Clare Boothe Luce.

NEW INTRODUCTORY LECTURES ON PSYCHOANALYSIS, by Sigmund Freud, translated by James Strachey. W. W. Norton & Co., Inc. ($4.50). Newly translated from the German and edited by James Strachey, these lectures first published in 1932 were intended as a supplement to Freud's earlier *Introductory Lectures on Psychoanalysis* (1915–1917) and as a synopsis of a number of important psychoanalytic subjects. They were addressed, as Freud remarks in his preface, "to the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multitude of educated people to whom we may perhaps attribute a benevolent, even though cautious, interest in the characteristics and discoveries of the young science." The volume forms part of the standard edition of Freud's writings under Strachey's general editorship.

THE COLLECTED MATHEMATICAL PAPERS OF HENRY JOHN STEPHEN SMITH, edited by J. W. L. Glaisher. Chelsea Publishing Company ($27.50). A two-volume reprint of the collected papers, first published in 1894, of H. J. S. Smith, Savilian Professor of Geometry at Oxford from 1860 to 1881. Smith was that rare bird, a fine classical scholar and a first-rate mathematician. It was a common story at Oxford that Smith, being uncertain after he had taken his degree whether he should devote himself to classics or to mathematics, solved his indecision by tossing a coin. Throughout his professional life he was not only admired for his intellectual abilities but also loved by his colleagues and by students in the university for his kindness, his equable manner, his wit and his willingness to give generously of his time to any person or cause that needed his help. Smith's mathematical output was not large, but it was elegant and of quality. It includes his celebrated report to the British Association for the Advancement of Science on the theory of numbers and also papers on geometry and elliptic functions—representing his major interests in mathematics.

AUTOMOBILES AND AUTOMOBILING, by Pierre Dumont, Ronald Barker and Douglas B. Tubbs. The Viking Press ($35). A picture history of automobiles and automobiling from the beginning to the late 1930's. The text is supported by 56 pages of vivid, unhackneyed photographs concerned with the natural history of cars and drivers and 200 renderings in color of such incomparable vehicles as the 35-horsepower Mercedes of 1901, the Fiat touring car of 1904, the 90-horsepower Renault of 1906 (which won the first Grand Prix), the Silver Ghost Rolls-Royce of 1908, the 28-horsepower Lanchester of 1909 (embodying the unprecedented, but later widely copied, ideas of its inventor), the Mercer Raceabout of 1913 (noted for its delicacy of control and ability to hold the road), the six-horsepower Peugeot Bébé, the nautical-looking Panhard and Levassor Sport of 1914 with its skiff body, the incomparable Stutz Bearcat of 1914, the exquisitely engineered Hispano-Suiza of 1921, the exotic Duesenberg Model J, the several impossible and magnificent Bugattis, the supercharged Alfa Romeo of 1930 (with its timeless perfection of form and fitness of purpose), the 4.5-liter Bentley (the last of the "vintage big fours") and so on and on. One comes away from this book with two convictions: first, that no car made today is mechanically better than or aesthetically equal to the great machines of 30, 40 and even 50 years ago; second, that this is the best book ever published on the subject. Buy it, even if you have to skip the next payment on your own set of wheels.

THE PRINCIPALL NAVIGATIONS, VOIAGES AND DISCOVERIES OF THE ENGLISH NATION, by Richard Hakluyt; edited by David Beers Quinn and Raleigh Ashlin Skelton. Cambridge University Press ($35). Hakluyt's two-volume collection of voyages, first issued in 1589, is a famous work of Elizabethan history and literature and a great chronicle of the adventures of the English navigators whose voyages did so much to make known the overseas lands. Many people are acquainted with the book, primarily through the second version that Hakluyt published in three volumes in 1598–1600 and that has often been reprinted. The later edition contains more material, but it was "sifted, scrubbed or pruned" so that the fresh flavor of the original was to some extent lost; if the second edition is more credible, the first is nearer to the events described and more vivid and effective. It is for this reason that the Hakluyt Society has prepared an uncommonly handsome facsimile of the 1589 edition, offering it with a useful bibliographical introduction by Quinn and Skelton and a new index. This is a desirable memento that should find a ready welcome among scholars, bibliophiles and cultivated readers.

PARMENIDES, by Leonardo Tarán. Princeton University Press ($10). This book on the pre-Socratic philosopher Parmenides gives the Greek text of surviving fragments of his writings together with a translation and extensive commentaries. Parmenides' doctrine of being, which insisted that nonbeing is impossible and unthinkable, that difference cannot exist, that process and change are illusory and therefore that all attempts to describe the world are impossible, was a source of king-sized headaches to Plato, Aristotle and other philosophers of antiquity and is no less baffling, however sterile it may seem, to modern thinkers. Tarán wades through the large literature of philosophers and critics and attempts to pin down exactly what Parmenides said and what he meant. A grueling but engrossing labor.

CATS OF THE WORLD, by Armand Denis. Houghton Mifflin Company ($5.95). An illustrated account of the 36 members of the cat family, including the lions, leopards and cheetahs of East Africa, the tigers and lions of India, the bobcat, lynx and jaguarundi of America and the Tibetan Pallas's cat. The author, who lives in Nairobi, has had extensive field experience.

Notes

SOCIETY AND SCIENCE, edited by Maurice Goldsmith and Alan Mackay. Simon and Schuster ($6). A better than average *Festschrift* honoring the appearance in 1939 of J. D. Bernal's influential book *The Social Function of Science,* with contributions by Lord Snow, P. M. S. Blackett, Peter L. Kapitza, Joseph Needham, J. B. S. Haldane, N. W. Pirie, R. L. M. Synge and others.

MECHANICS, MOLECULAR PHYSICS, HEAT, AND SOUND, by Robert Andrews Millikan, Duane Roller and Earnest Charles Watson. The M.I.T. Press ($3.45). A soft-cover reissue of one of the best and most widely used physics textbooks, its particularly lucid exposition made doubly attractive by abundant historical information.

MR TOMPKINS IN PAPERBACK, by George Gamow. Cambridge University Press ($1.95). In this paperback are combined two of Gamow's well-known and well-liked scientific whimsies, *Mr Tompkins in Wonderland* and *Mr Tompkins Explores the Atom,* brought up to date and including more stories on advances in physics and related fields (fission and fusion, the steady-state universe and elementary particles) that were made after the books were originally published.

CARDANO: THE GAMBLING SCHOLAR, by Oystein Ore. Dover Publications, Inc. ($1.60). A paperback reprint of a good biography of the 16th-century physician, mathematician, astrologer, alchemist, gambler and whatnot, reviewed at length in these columns in 1953.

THE AMERICAN SOLDIER: ADJUSTment during Army Life and The American Soldier: Combat and Its Aftermath, by Samuel A. Stouffer and others. John Wiley & Sons, Inc. ($5.90). A republication in inexpensive form of the first two volumes of a noted series of studies prepared and edited under the auspices of the Social Science Research Council.

Space, Time and Architecture: The Growth of a New Tradition, by Sigfried Giedion. Harvard University Press ($12.50). The fourth edition of this widely appreciated work includes Giedion's essay "Architecture in the 1960's: Hopes and Fears."

Electrons and Waves, by John R. Pierce. Doubleday & Company, Inc. ($1.25). The first eight chapters of Pierce's *Electrons, Waves and Messages*, originally published in 1956 and now brought up to date, this little paperback is a good introduction to the study of electronic techniques and communication.

The Holmes-Einstein Letters, edited by James Bishop Peabody. St. Martin's Press, Incorporated ($12.50). An urbane, gracious and reflective series of exchanges (1903–1935) between two thoroughly civilized men: Justice Oliver Wendell Holmes and Lewis Einstein, an American diplomat.

Handbook of Chemistry and Physics. The Chemical Rubber Company ($16). The 46th edition of this indispensable handbook has been enlarged and revised.

Studies on Oceanography, edited by Kozo Yoshida. University of Washington Press ($20). A *Festschrift* dedicated to Koji Hidaka, the first director of the Ocean Research Institute of the University of Tokyo and an important contributor to oceanography.

Advances in Astronomy and Astrophysics: Volume III, edited by Zdeněk Kopal. Academic Press Inc. ($14). Included in the third volume of this series are articles ranging from such topics as the abundance of the elements in the solar atmosphere to the main features of modern cosmology.

Oriental Architecture in Color, by Werner Speiser. The Viking Press ($22.50). A survey of Islamic, Indian and Far Eastern architecture from Jerusalem to Kyoto with a brief text by Speiser and 112 colorplates.

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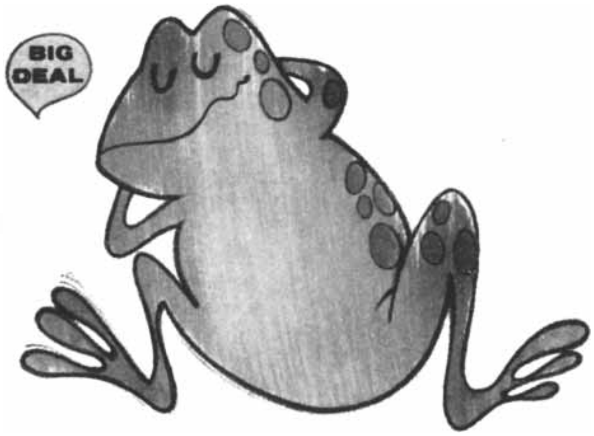

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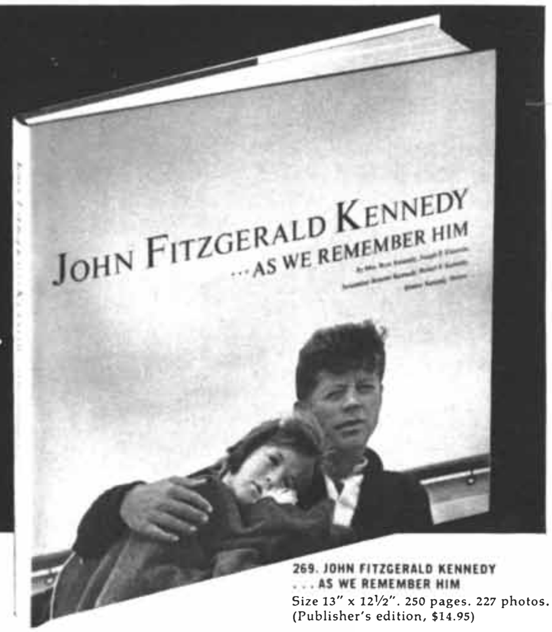

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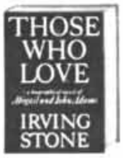

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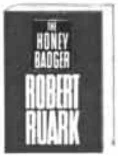

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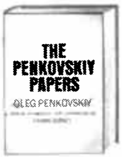

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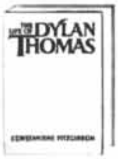

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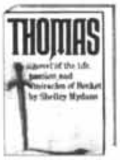

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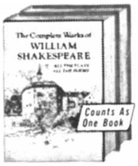

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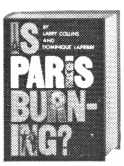

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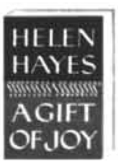

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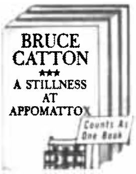

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