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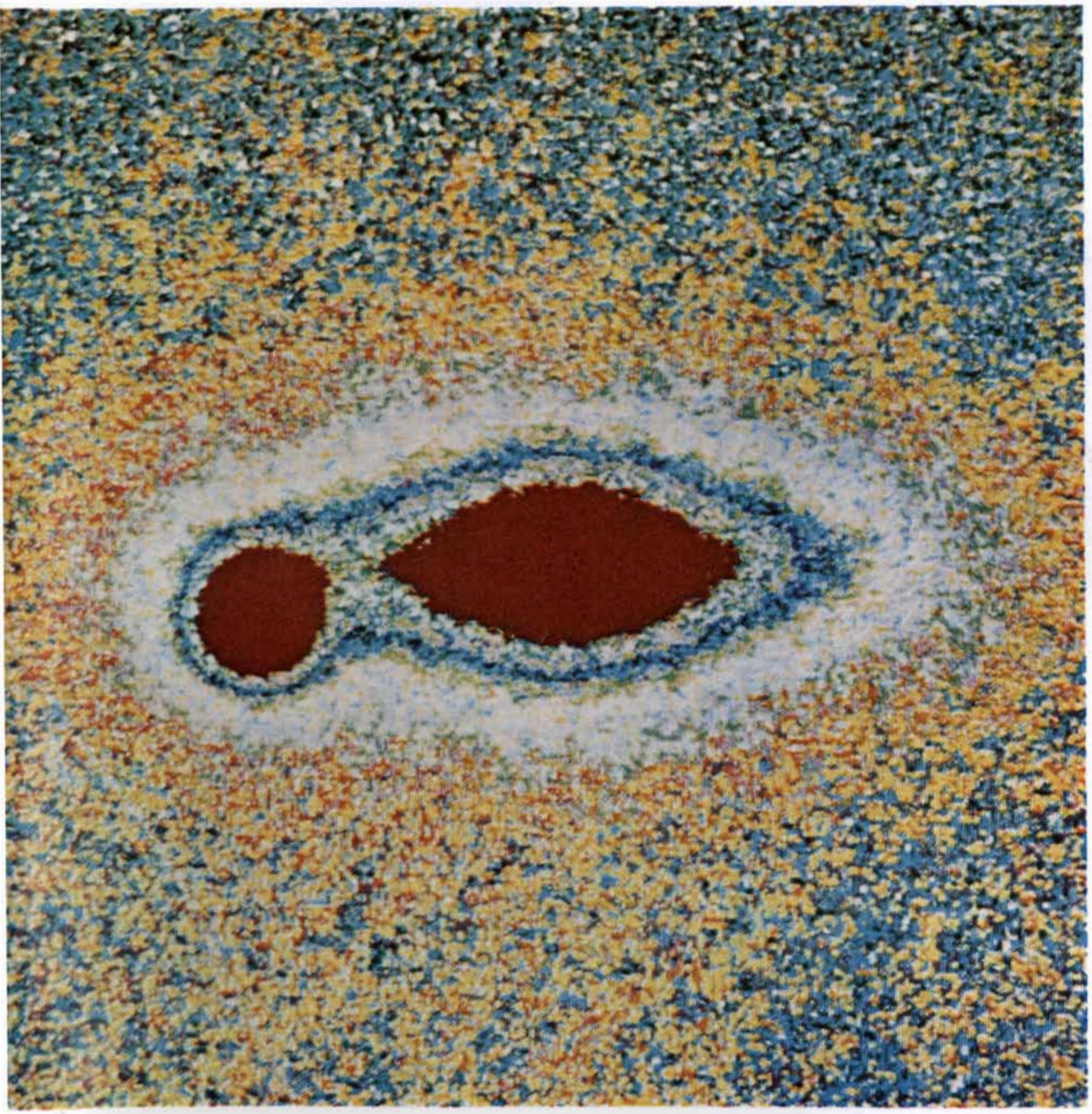

EXTRAGALACTIC SUPERNOVA

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December 1976

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A gift bottle of Cutty Sark is a terrific way
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But why forget yourself?
This year, buy an extra bottle of Cutty.
So while you're doing unto others,
you can do unto yourself, too.

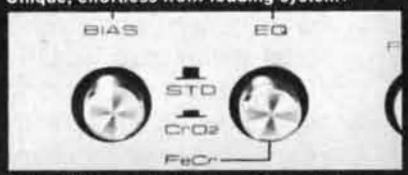
Pioneer's new 9191...the best cassette deck under $450† that money can buy.

Here is a magnificent cassette deck with specifications that are beyond what our industry had been aware were possible; specs that surpass anything that a deck of this price, performance and quality has ever been able to come up to before. Unbelievably low wow and flutter; solenoid controls that operate at a touch with almost magical precision, and a unique, truly-visible horizontal front loading system by which the cassette is effortlessly set into place with two fingers, are only a few highlights.

Pioneer's new 9191 incorporates a cascade of features and innovations: automatic CrO_2 tape detector and indicator light; an illuminated panel scale that lets you see at a glance the amount of tape remaining on a cassette; and an advanced memory rewind circuit that permits quick and easy location of (and automatic re-start from) any point on a cassette tape. It also has two independent drive motors, including an electronically-controlled DC unit for recording and playback.

Our engineers took into consideration the many types of tapes available and included superior bias and equalization circuitry and switching (in addition to the the automatic CrO_2 detection system) so that the 9191's recording capability is optimized for any kind of cassettes you want to use. And, of course, there's built-in Dolby B* to bring the 9191's S/N ratio up to 62 dB, even with standard tapes. We've also included separate mic/line mixing, and an extra pair of input and output jacks.

Unique, effortless front-loading system.



Selectable equalization and bias switches.

By now you realize that here is a cassette deck rivalling the performance of decks costing hundreds of dollars more; a deck whose controls make it respond faster than many reel-to-reel machines, and which offers greatly-extended frequency response and dynamic range. And it's the only front-loading, front-control, stackable deck to have all the features we've mentioned.

But of all the ingredients that make up the 9191: performance, reliability, style and features, the most important of all is its value. We set out to build a cassette deck that was better, but less costly, than any deck built previously. We know we have succeeded. We know that you'll agree when you see and handle the Pioneer CT-F9191 at your Pioneer dealer.

CT-F9191 Specifications:

Frequency Response: Standard, LH tape: 25-16,000 Hz (35-13,000 Hz ±3dB); CrO_2 tape: 20-17,000 Hz (30-14,000 Hz ±3dB)

Signal-to-Noise Ratio: Dolby OFF: More than 52 dB; Dolby ON: More than 62 dB (Over 5,000 Hz, Standard and LH tapes) More than 66.5 dB over 5,000 Hz with CrO_2 tape

Harmonic Distortion: No more than 1.7% (OdB)

Wow and Flutter: No more thas 0.07% (WRMS)

U.S. Pioneer Electronics Corp., 75 Oxford Drive, Moonachie, New Jersey 07074. West: 13300 S. Estrella, Los Angeles 90248 / Midwest: 1500 Greenleaf, Elk Grove Village, Ill. 60007 / Canada: S.H. Parker Co.

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* Dolby is a trademark of Dolby Laboratories, Inc. †The value shown is for informational purposes only and includes a cabinet with walnut grained vinyl top and side panels. The actual resale price will be set by the individual Pioneer dealer at his option.

Instant photography From under

Name your price and pick your Polaroid camera. They all have different features, yet all have one thing in common. Each gives you the excitement of seeing beautiful pictures right after you take them.

Polaroid's Electric Zip, the teenager's favorite, for color pictures in a minute or black-and-white in seconds. "If you want it, Zip! you've got it!" Just $23.95*

The Super Shooter takes pictures in 2 sizes and uses 5 different kinds of instant film, from the least expensive to our beautiful Super Color. Electric eye and electronic shutter give you automatic exposures (for all 5 films). Sharp 3-element focusing lens and built-in flashcube holder with automatic advance. Wait only 60 seconds. Pay only $28*

SX-70 photography starts with the $66 Pronto!, our easiest instant camera ever. Little and light, you just set the distance and shoot. Pronto! hands you the picture already developing. In minutes, you have a big 3-1/8" x 3-1/8" finished color print. Takes the new Superclear SX-70 film (with a fresh battery in every 10-shot pack). Takes 10-shot FlashBar. Automatic exposure control. $66*

Pronto! RF has all the advanced Pronto! features and adds a built-in rangefinder for more accurate focusing. Also takes all Pronto! accessories, such as self-timer and tripod mount so you can get into your own pictures. $79.95*

Choose one of the history-making SX-70 Land cameras, that focuses from 10.4" to infinity and folds into a slim, elegant shape to slip into pocket or purse. All three use the new Superclear SX-70 film with Colorlock dyes that resist fading; *SX-70 pictures last.*

With the SX-70 Model 3, in black

for everyone. $24. From Polaroid.

plastic and deep tan Porvair, you get all the deluxe SX-70 features except through-the-lens viewing and the new Alpha electronics. Same electronic shutter system, same SX-70 motor drive, same amazing SX-70 lens. $132*

For through-the-lens viewing, give the SX-70 Model 2, in brown Porvair and off-white plastic. $165*

Or give the brand new SX-70 Alpha 1, Polaroid's finest camera, made even better. Outdoors, an electronic shutter sets exposures automatically. Indoors, a special monitored flash makes final split-second exposure corrections. (The SX-70 Alpha 1 ingeniously prevents wasting a picture or a flash.) Alpha 1 can be focused 3 different ways: through the single lens reflex viewfinder, or with the split-image rangefinder; or by setting the distance. In genuine leather and a velvety chrome finish, with leather neck strap and built-in tripod mount. Give Polaroid's most revolutionary camera ever. The new SX-70 Alpha 1. $210*

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ARTICLES

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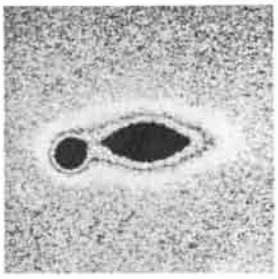

THE COVER

The picture on the cover is a brightness contour map of a supernova discovered in June, 1975, in a galaxy in the constellation Ursa Major (see "Supernovas in Other Galaxies," by Robert P. Kirshner, page 88). The supernova, a catastrophic explosion of a star at the end of its life, is the round red area at the left; the main body of the galaxy is the elongated red area to the right. The map was constructed from a photographic plate of the object made by Howard French at the Kitt Peak National Observatory in Arizona. The density of the plate was measured with a microdensitometer and was analyzed as though the plate were made up of tiny squares 20 micrometers on a side, with the density of each square being assigned a number. The numbers were then used to generate a display on a digital color television screen that is part of the Kitt Peak Interactive Picture Processing System. Each color corresponds to a density number; here red represents the brightest areas and blue the dimmest. It can be seen that the supernova was about as bright as the entire parent galaxy.

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Cover photograph courtesy of Robert P. Kirshner, University of Michigan

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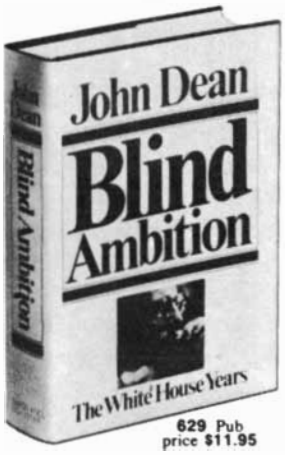

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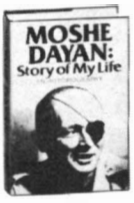

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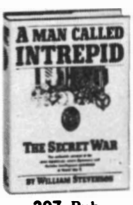

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LETTERS

Sirs:

In his article "Center-Pivot Irrigation" [SCIENTIFIC AMERICAN, June] William E. Splinter describes the agricultural revolution that has resulted from the use of center-pivot irrigation systems throughout the western Middle West. We should like to put forward a concern about a further cost of such systems: the removal of many hundreds of miles of shelterbelt trees.

Shelterbelts have been recognized as the most successful large-scale weather-modification activity ever attempted. Growing out of the Dust Bowl drought years of the 1930's, this program established tree plantings to stabilize the soil, reduce soil-moisture loss, increase soil moisture through snow accumulation and in general improve the microclimate of croplands in the vicinity of the belts. Recently a combination of factors has led to a drastic reduction in the acreage of shelterbelt trees. Other methods of reducing wind erosion have been devised, involving the management of crop residues and new types of tillage. All such methods require enough moisture to grow a crop, and several successive dry years make them much less effective.

Moisture conditions have been generally favorable since the 1960's in North Dakota, South Dakota, Nebraska, Kansas and Colorado, so that establishing annual crops has not been a problem. And since cropland is valuable, reduction of nonproductive land has been the rule. Moreover, although center-pivot irrigation systems can do many things, they cannot run over 30-foot trees. Thus the trees are being removed.

The value of tree shelterbelts is much like a savings account. On a dollar-for-dollar basis there are better investments, but trees that are planted and grow during the good years will be there during the dry and windy years to protect the land from disaster. The trees become increasingly valuable as drought continues to deplete ground-water supplies and to render the irrigation systems, if they can operate at all, absurdly expensive and energy-consumptive.

A 1975 General Accounting Office report ("Action Needed to Discourage Removal of Trees that Shelter Cropland on the Great Plains") raised concerns about the removal of the trees. The report stated: "Unless actions are taken to encourage farmers to renovate and preserve existing windbreaks rather than remove them, an important resource which has taken many years to develop could be lost and adjacent cropland could erode and become less productive." Center-pivot irrigation systems are only one of the reasons for removing trees; others are current economics, a general lack of knowledge of the long-term benefits of the trees and fading memories of skies filled with dust....

DOUGLAS G. FOX

RALPH A. READ

RICHARD W. TINUS

Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colo.

Scientific American, December, 1976; Vol. 235, No. 6. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and secretary; George S. Conn, treasurer; Arlene Wright, assistant treasurer.

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Advertising correspondence should be addressed to C. John Kirby, Advertising Director, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017.

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Sirs:

When the present offers illumination of the distant past, it seems a shame to ignore it.

In his review of bull-leaping as it was depicted in ancient Crete and Greece ["Science and the Citizen"; SCIENTIFIC AMERICAN, August] John G. Younger of Duke University seems to have overlooked a version of that ancient sport that continues to flourish in the *course landaise,* a kind of bullfighting peculiar to the Landes region of southwestern France.

An inevitable part of the *course landaise* is the performance of a *sauteur,* who, if he is particularly skillful, will demonstrate several ways of leaping over a charging bull. (Actually in this kind of bullfighting it is the female animal that is fought, but the horns are just

When it comes to buying a 35mm SLR, foresight is less expensive than hindsight.

The time to find out what you need in a 35mm SLR is before you buy it, not after.

Because a camera that meets your needs is a good buy. And a camera that doesn't is a bad buy at any price.

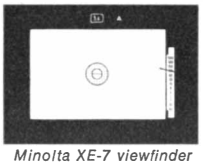
Know thyself. First of all, look ahead to what you'll want to do with the camera. Most manufacturers, including Minolta, offer a tempting array of features. To name a few: interchangeable finders and viewscreens, motorized film winding, self-timers, multiple-exposure capability and automatic exposure control. If you'll be using them, fine. If not, save yourself some money by cutting out the frills. Don't buy more camera than you need. Or less.

Match-needle or electronic auto-exposure? Minolta makes both kinds, so our only concern is that you get what's best for you.

A match-needle camera costs less. To set exposure, you line up two needles in the viewfinder. It's easy, fast and accurate, but you do the work. Minolta's match-needle models, the SR-T 200, the SR-T 201 and the SR-T 202, differ in price, according to their operating features.

Minolta's electronic automatic models are the professional XK, the deluxe XE-7 and the economical XE-5. In these cameras, shutter speeds are controlled electronically with unprecedented precision. Even if the light changes the instant before you shoot, the camera will set itself for correct exposure. Among Minolta electronic SLR's, you get a wide choice of features, including interchangeable viewfinders and focusing screens, shutter speeds to 1/2000th of a second, and multiple-exposure capability.

How much information should the viewfinder display? The more information in the viewfinder, the more you know about the technical details of how the camera is taking the picture. If this means a lot to you, pay the extra cost. If not, save some more money by getting a simpler model.



Minolta XE-7 viewfinder

The important thing about Minolta SLR's is that in every single one, you can compose, focus, set exposure and shoot without ever looking away from the viewfinder. So you won't miss shots of even the fastest-moving subjects.

How does the camera feel and sound? This can tell you a lot about how well thought out the design is. A camera shouldn't take "getting used to." Your fingers should fall naturally and comfortably into place over the controls.

Advance the film wind lever. If a new camera has a "grainy" feeling, how will it feel after a couple of thousand shots?

How about noise? Close machine tolerances and careful damping of moving parts in Minolta cameras give you a noticeably smoother, more solid response when you push the shutter button. And Minolta's automatic SLR's have a newly designed electronic shutter that's a joy to hear because you almost can't hear it.

The lens system. You need a choice of lenses broad enough to meet your present and future needs. Minolta offers almost 40. From a 7.5mm "fisheye" to a 1600mm super-telephoto.

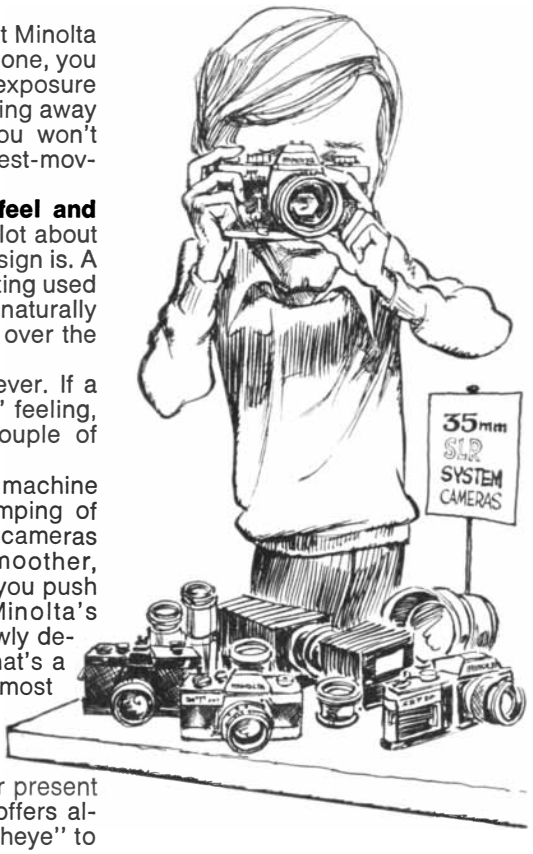
Minolta

The more you know about cameras, the more you'll want a Minolta.

How easy is it to change lenses? You shouldn't miss any shots while changing lenses. So Minolta has developed a patented bayonet mount that locks on in less than a quarter turn, instead of the three or more turns required by a screw mount.

And unlike others, the Minolta bayonet mount doesn't require realignment of f/stops every time you change lenses.

How do you judge craftsmanship? Take a close, careful look at the details. Everything should be tucked in neatly. Finishes should be even and unmarred. No machining marks should be visible, even inside.



Cameras have reputations. Check them out. By all means, ask your friends about Minolta. Since it's the largest-selling imported camera brand in the U.S., chances are someone you know owns one.

If you'd like more information about Minolta 35mm SLR's, write to Minolta Corporation, 101 Williams Drive, Ramsey, N.J. 07446. In Canada: Anglophoto, Ltd., P.Q.

Conversation Pieces

PLANETARY CROP-WATCHER WITH 20/20 VISION

Thematic Mapper scheduled to fly in 1980 aboard Landsat-D spacecraft will be in sun-synchronous orbit at 705 km altitude, scanning a swath 185 km wide and covering all inhabited areas of the earth.

Forecasting crop yields is still more of an art than a science. No electronic system, however sophisticated, can yet match a farmer's feel for how his crops are doing. But individual assessments like "pretty good" or "we'll have a bumper crop if the weather holds" can't be used effectively for worldwide or even regional forecasts. They don't fit into a computer, and they take too long to compile and analyze.

What's needed is millions of precise, numerical estimates of crop status flowing steadily into the computer on an acre-by-acre basis. This calls for a satellite-borne system which provides a truly synoptic view of the earth's arable areas. NASA's Landsat, in orbit since 1972, has been providing this kind of data. NASA is now preparing to provide a much improved capability to the world's users of Landsat data.

This next generation Landsat sensor system, called Thematic Mapper, is now in the study phase. This new system will provide improved spatial and spectral resolution over the present system. It will be able to discriminate more effectively between different crops, stages of growth, and sick and healthy vegetation. Besides crop watching, it will be able to survey forest resources, detect changes in land use, monitor rangelands for better livestock management, and help in watershed and water use management.

Some additional growth capabilities will be built into the Thematic mapper design under study by TRW Systems and Perkin-Elmer. Because of its unique rotary scanning system, the scan is unidirectional and the sensor output is inherently linear. This means simplified data processing on the ground, faster status reporting, and thus an overall reduction in system operating costs.

Simplified ground data processing is particularly important. It means that low-cost ground stations can be set up around the world. They'll be able to take data on local crop conditions directly from the satellite as it passes overhead; no need to go through a central receiving station. Such reports will become even more valuable when they can be coordinated with long-range weather forecasts.

The Thematic Mapper is one of many ways that TRW is working to improve space technology as a tool to give us a better understanding of our earth and man's impact on it.

TRW is a worldwide leader in electronics, defense, & energy systems and in computer-related technology for information management & systems control.

TRW

DEFENSE AND SPACE SYSTEMS GROUP

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as dangerous and the urge to kill is just as strong.) The *sauteur* may meet the animal's charge simply by jumping high enough to clear the horns on his way up and the flanks on his way down; he may execute a forward flip that deposits him back on the ground just after the animal has passed under him, or he may leap high and forward with his arms widespread, seemingly flying over his four-footed opponent.

This last maneuver is called a *saut de l'ange,* and in photographs it looks exactly like the depictions of bull-leaping preserved on certain ancient Greek seals: the leaper is in a "static... pose above the bull. The leaper seems to float there horizontally." That description by Younger was intended to indicate the impossibility of such a leap, and to prove that such depictions must have been based on descriptions or conventions rather than on eyewitnessed events.

This conclusion is called into question by the photographs of the *saut de l'ange,* which appear regularly in French newspapers during the *course landaise* season. There may have been no bull-leapers left in Greece after 1300 B.C., as Younger contends, but there are some very good ones alive and leaping in France today.

WILLIAM C. WEES

Department of English
McGill University
Montreal

Sirs:

Concerning the famous "medieval woodcut" of the traveler poking his head through the starry sphere ["The Curvature of Space in a Finite Universe," by J. J. Callahan; SCIENTIFIC AMERICAN, August], I erred in telling the editors that it was first published in 1907. Arthur Beer of Cambridge, England, informs me that it first appeared in 1888 on page 163 of Camille Flammarion's *L'Atmosphère: Météorologie Populaire.* It is quite likely that Flammarion, an experienced artist as well as an astronomer and science popularizer, himself originated the design. I took my previous information from a 1957 article by Ernst Zinner, in which the German historian of astronomy reported his unsuccessful efforts to find an earlier publication. Zinner's search included Flammarion's prolific astronomy popularizations but overlooked the one on meteorology.

OWEN GINGERICH

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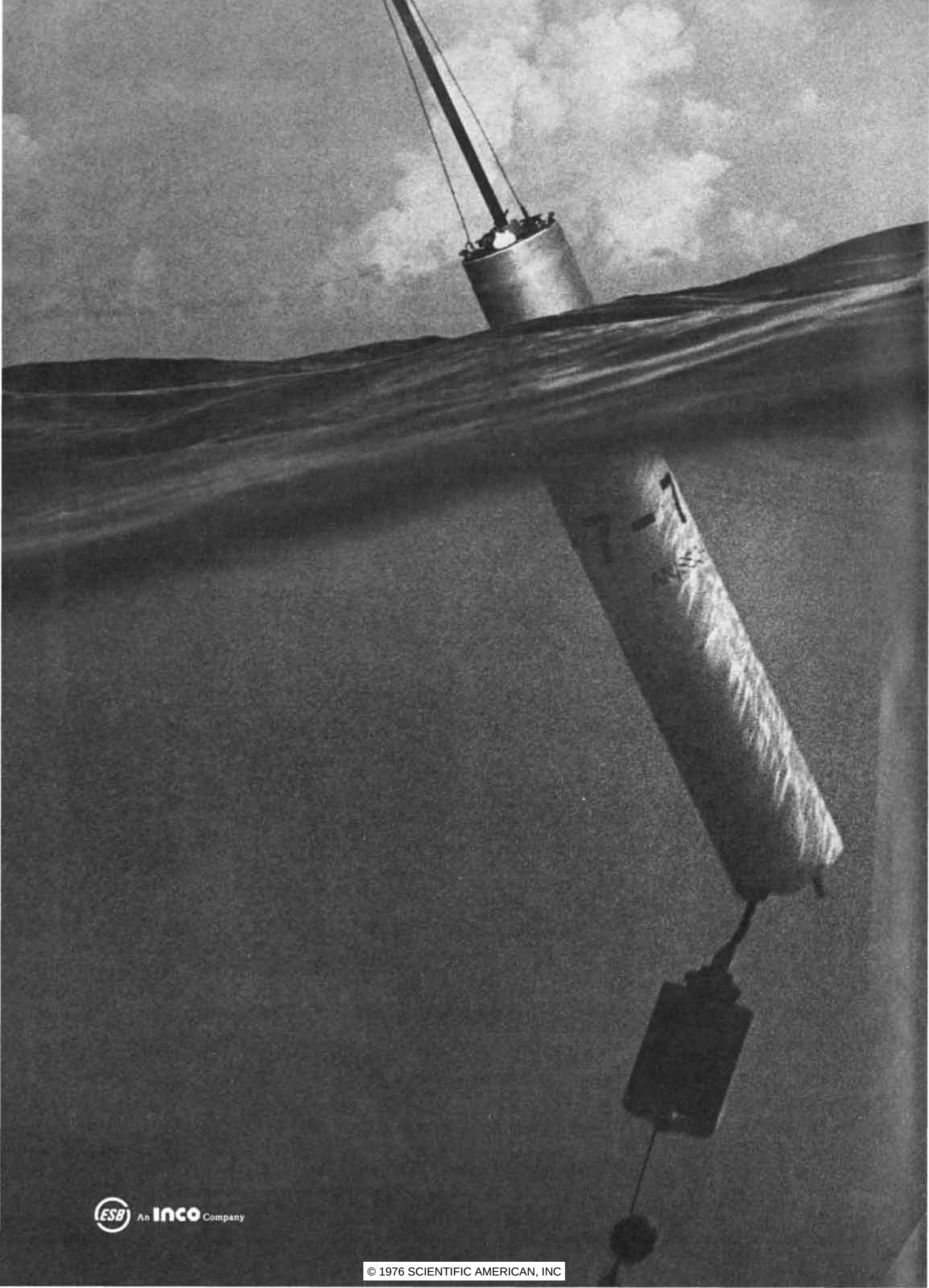


The best ideas in sonobuoy batteries come from ESB.

The idea: make a less expensive version of the silver, water-activated battery that operates a sonobuoy (the sophisticated sonar device featured here that detects submarines).

And do it without sacrificing capacity. Or efficiency. Or dependability.

The result: our Wisco Division's magnesium lead chloride battery.

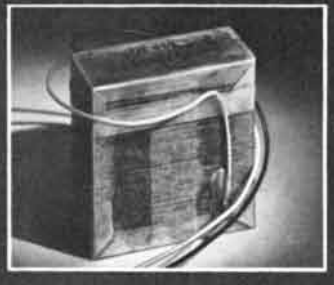
Each year the Department of Defense drops thousands of sonobuoys into various oceans.

Until we provided our alternative, the sonobuoy batteries they used were made with silver. That made them very expensive.

And because sonobuoys are not retrievable, it also meant that precious silver was being wasted on the ocean floor.

You can guess the rest. Our scientists found a way to make a silver-free battery, using lead instead. Which substantially lowered the cost. And prevented the unnecessary loss of a valuable metal.

Our magnesium lead chloride battery is the first of its kind. And ESB is the only major source of silver-free batteries being used in sonobuoys by the U.S. Government.



If you'd like to learn more about our ideas in energy, write: Communications Department, ESB Incorporated, 5 Penn Center Plaza, Philadelphia, PA 19103. Or call: (215) 564-4030.

Ideas in energy.

ESB

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

DECEMBER, 1926: "The relation of the United States to the debtor nations was never more happily put than in President Coolidge's Memorial Day speech at Arlington. The President referred to the loans made to foreign governments and foreign enterprises for the purpose of reestablishing their public credit and their private industry. He said, 'By such action we have not only discharged an obligation to humanity but have likewise profited in our trade relations and established a community of interests which cannot be but an added security for the maintenance of peace. In so far as we can confirm other people in the possession of profitable industry, without injuring ourselves, we shall have removed from them that economic pressure productive of those dissensions, discords and hostilities which are a fruitful source of war. It has been in accordance with these principles that we have made generous settlements of our foreign debts. It has been thought wise to extend the payment of our debts over a long period of years, with a very low rate of interest in order to relieve foreign peoples of the burden of economic pressure beyond their capacity to bear.'"

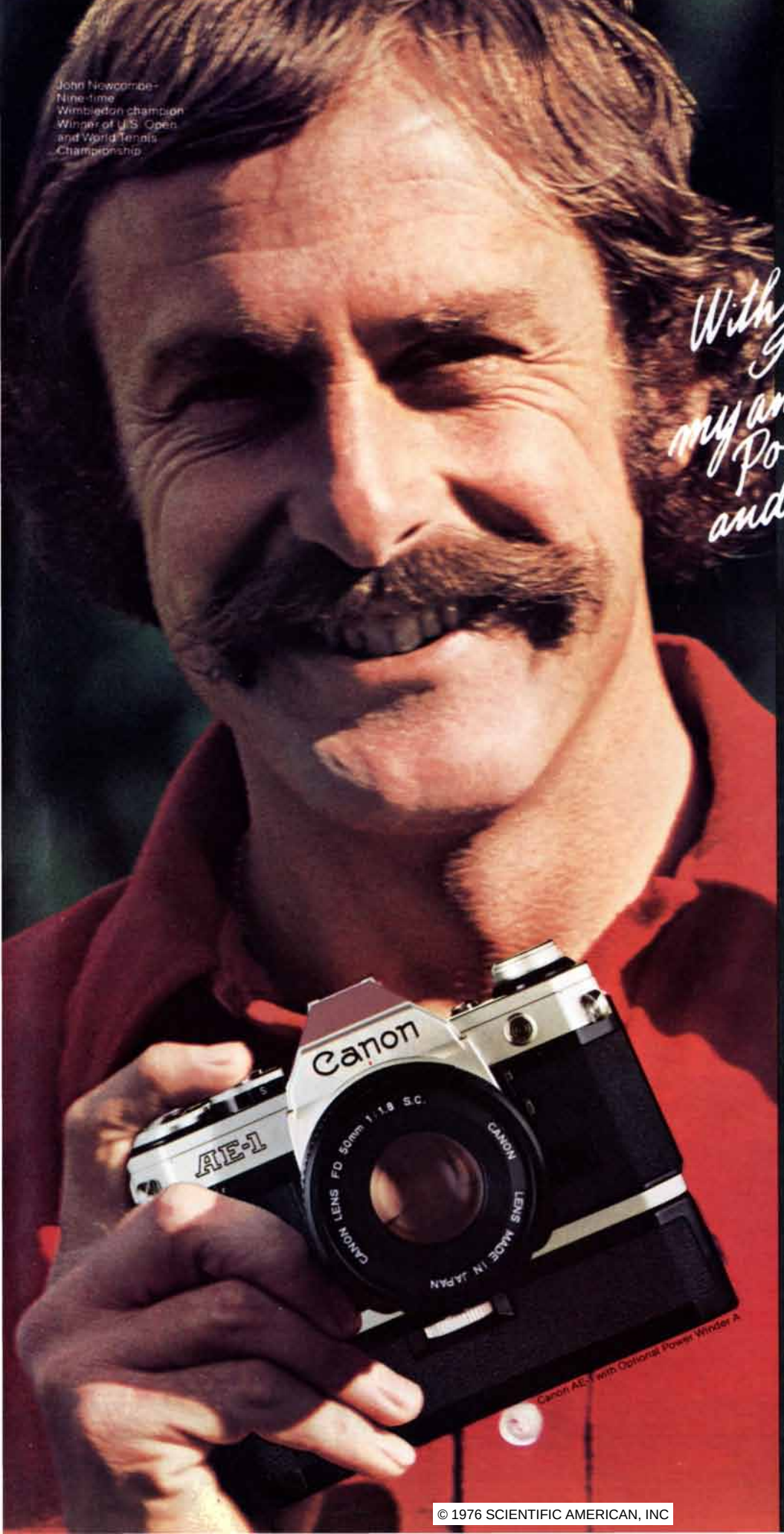
"The Secretary of the National Research Council, Dr. Vernon Kellogg, states that we can no longer depend upon scientific research in Europe for future development. He thus emphasizes Secretary Hoover's recent call for the promotion of research in pure science in America. Germany, France and other Continental countries have for generations led the world in the study of pure science, and the United States has profited by the results. But Europe has received a staggering set-back in its pure science research work as a result of the stringent economic conditions imposed since the World War. 'Everywhere,' says Dr. Kellogg, 'I have met with the cry, "We have little money for research; what are you in America going to do?" We owe it to ourselves, nay, we owe it to the world at large, to turn a larger share of our enormous post-war wealth into the channels of pure science research."

"The installation of brakes on airplane wheels is proving very useful. The brakes shorten the landing run, do away with the necessity of ground tackle or of men hanging on to the wings at the start of the takeoff and when acting independently on either wheel facilitate steering on the ground. The Sauzedde Wheel Company has now brought out a wheel for airplanes in which the brake mechanism is an integral part of the wheel. A wire, usually enclosed in the steel-tubing struts of the landing gear, transmits the force to the brake from the rudder-bar pedal."

"A new method of cheaper synthesis of high-grade motor fuel in Germany may go far toward the solution of the motor-fuel problem in the future. The Berlin professor Franz Fischer, who recently devised means of making liquid fuel synthetically from coal products, has now simplified his process so that he can dispense with the costly high-pressure apparatus that has stood in the way of its commercial development. Coke and coal are almost completely gasified when steam is led over them at high temperature, and water-gas, a mixture of carbon monoxide and hydrogen, is formed. The Badische Analin und Soda Fabrik first succeeded in commercially synthesizing liquid fuels from this gas mixture in Germany by means of Professor Fischer's early methods, in which pressures of 1,500 pounds per square inch or more were employed. By his new process Professor Fischer has succeeded in synthesizing gaseous, liquid and solid hydrocarbons from carbon monoxide and hydrogen at ordinary pressure. Hitherto all reduction of carbon monoxide without pressure yielded methane, but Fischer found that by using an iron-zinc oxide catalyzer more complicated products were formed."

SCIENTIFIC AMERICAN

DECEMBER, 1876: "Although failure has been the fate of every attempt thus far made to navigate the air by mechanical devices, the problem has by no means been given up as hopeless. Certain experiments, made at the expense of the Aeronautical Society in England, to determine the exact lifting pressure of air currents directed against a plane inclined at different angles, have obtained results that are especially promising. The plane used was a steel plate a foot square, and the substitute for the resistance occasioned by the passage of a body at high speed through the air was the blast of a powerful fan blower. The pressure on the plate was 3¼ lb., indicating a wind velocity of about 25 miles per hour. Inclined at an angle of 15 degrees, the plate felt a lifting pressure amounting to 1/2 lb. The chief thing that remains to be done for the successful solution of the problem of flight is therefore to drive a sufficiently broad-bottomed car at a speed of, say, 40 to 60



With the AE-1, I've lost my amateur standing. Point and shoot, and you're a pro.

Professionalism highlights everything John Newcombe does on the tennis court. But when it comes to taking pictures, he wants a camera that gives great results, but doesn't take a degree in math to operate. That's why he likes the Canon AE-1.

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European style with a big-car feeling.

In practically no time at all, the Aspen sedan has accomplished what many have tried to deliver. A roomy, smaller car with a big-car feeling . . . at a very appealing price. Its well-bred European looks are not deceiving. For Aspen's comforts include total interior room that exceeds that of a Cadillac Seville. And the Aspen ride—based on its unique suspension system—surprises with a comfort and smoothness you'd expect from a larger, more expensive automobile. But the original idea behind Aspen was to give you just that: a smaller car with all the civilized big-car touches. Luxury features? There's a long list of big-car options: from power seats and windows to automatic speed control. And most unbelievable of all is the Aspen sedan's low base price. It's as unbelievable as the Aspen sedan itself. Buy or lease one today and see.

The small car at a small price...the unbelievable ASPEN

Dodge

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miles an hour by means of an apparatus acting on the air. At this velocity the resistance of the air would support the car, at the cost of a relatively small part of the driving force."

"We have before us the detailed narrative of the English expedition that has lately returned from the Arctic regions. The sledge parties from the *Alert* reached the highest northern point ever attained, and only turned back when further progress toward the pole became impossible owing to the roughness of the ice and the terrible cold. When all had come back to the ships, Captain Nares expressed the opinion that the heroic devotion of officers and men had secured for the expedition complete success. While the pole had not been reached, the impracticability of anyone's ever attaining it had been placed beyond doubt."

"How does the typhoid fever poison gain admission to the human body? Undoubtedly there are two principal sources, namely the air we breathe and the water we drink. A large number of well-authenticated histories have now established the fact that the fever may result from gases emanating from privies, sewers, etc., that have been the receptacle of the excrement of typhoid patients, and also from drinking water from springs and wells that have become contaminated by matters from adjoining privies and cesspools. The exact nature of the typhoid fever poison, however, is still unknown."

"Some time ago a number of enthusiastic Frenchmen conceived the idea of presenting a monument to the people of this country in commemoration of the ancient friendship of the two republics. Meetings were held in Paris, a subscription list was opened, and finally it was decided that the monument should be an immense statue, more than 200 feet high, to be erected in New York harbor. The design is 'Liberty Illuminating the World,' and in harmony therewith the hand of the figure holds a torch with a gilded flame. M. Bartholdi, a celebrated French sculptor, was commissioned to execute the work, and his operations have progressed as far as the completion of one hand and fore arm, which are at present erected on the grounds of the Centennial Exposition in Philadelphia. Now, however, there is a hitch in the money matter. It appears that it has been left to the people of New York to erect the pedestal and also to pay part of the expense of making the statue, and so far our citizens have failed to respond to the call upon their purses. Meanwhile in Philadelphia it has been proposed that if New York thus virtually declines the gift, Philadelphia will secure it for her inland harbor."

Hear the light.

Today, communications may be at the threshold of another revolution in technology.

Someday soon, when you make a phone call, your voice may be carried between telephone offices as pulses of light over a hair-thin glass fiber.

We call this new technology lightwave communications.

Less Cost, Less Space:

Lightwave communications has the potential for carrying enormous quantities of information—from phone calls to business data to TV programs—at low cost. And it can do it in much less space.

Right now, we're testing an experimental system that can carry nearly 50,000 phone calls in a cable of glass fibers not much thicker than a clothesline. It could do the work of several copper cables, each as thick as your arm.

That will allow us to save space in the crowded cable ducts under the streets of many of our cities. Which in turn will lessen the need to add new cable ducts to expand service.

But even carrying that many calls uses only a fraction of a light beam's capacity.

So it will give us plenty of room to grow.

To make lightwave communications possible, the people at Bell Labs and Western Electric attacked a number of problems simultaneously.

What Had to be Done:

What kind of problems?

Creating some of the most transparent glass the world has ever known.

Developing techniques to draw the glass into highly precise fibers which, despite their tiny size, have a complex internal structure that keeps the light from leaking out.

Devising ways to protect the delicate fibers from damage, to make them into cables strong enough to pull through underground ducts, and to splice them—a hundred or more at a time.

To generate the light carried by the fibers, they developed a tiny, solid-state laser smaller than a grain of salt. (Today's design is expected to operate continuously for ten years or more.)

To put information onto the light beam, they designed equipment that turns the tiny laser on and off millions of times a second.

And they developed repeaters to regenerate the light signal along its way, as well as photodetectors at the receiving end to convert the light back into an electrical signal that can travel throughout the telephone network.

We think lightwave communications may prove a long step forward in the development of communications.

We may put it to use in the early 1980's to relieve cable congestion between major switching centers. For special applications, we may use it even sooner.

And it may someday carry business data, visual communication services and facsimile transmission into your home and office.

Seeing to It:

Innovations from Bell Labs and Western Electric are put to work by your Bell telephone company. That's another reason you have the most reliable, least expensive telephone service in the world.

To keep it that way, one of the things we're doing is seeing to it that before long you'll be hearing the light.

One of a series of messages to keep you informed of how telecommunications technology is changing our world—and the part Bell Labs, Western Electric and your Bell telephone company are playing in it.

Bell Laboratories/Western Electric

THE AUTHORS

ELI GINZBERG ("The Pluralistic Economy of the U.S.") is chairman of the National Commission for Manpower Policy. Born in 1911, he has lived all his life in New York and received his bachelor's, master's and doctor's degrees from Columbia University. He is now A. Barton Hepburn Professor of Economics at the Graduate School of Business at Columbia and Director of Conservation of Human Resources. Ginzberg has been an adviser on manpower for the past seven presidents, beginning with President Roosevelt. He is the author of a number of books, including *The Pluralistic Economy*. His latest book, *The Human Economy,* published this year by McGraw-Hill, outlines his basic philosophy of human resources and manpower. Since World War II Ginzberg has also been engaged in studies of medical economics; in 1969 he published a book on the subject titled *Men, Money and Medicine.* "I lead a pluralistic life," he writes, "being a pure urbanite during the academic year and then spending three months every summer on Martha's Vineyard doing my basic work and recharging my batteries."

WILLIAM P. BEBBINGTON ("The Reprocessing of Nuclear Fuels") retired in 1975 after spending 35 years with E. I. du Pont de Nemours and Company. He joined Du Pont after receiving his bachelor's degree in chemistry and his doctorate in chemical engineering from Cornell University. During World War II he worked on the design of heavy-water plants for the Manhattan project. From 1945 until 1950 he was involved with economic studies and with planning heavy-water plants. For two years thereafter he worked with the Atomic Energy Division of Du Pont on the design of heavy-water plants. In 1952 he became Technical Superintendent of the Savannah River plant for the production of heavy water. There he remained in several different capacities, retiring from his final position as General Superintendent of the Works Technical Department. Bebbington's major interests outside of nuclear technology are botany and plant ecology.

OLGA EIZNER FAVREAU and MICHAEL C. CORBALLIS ("Negative Aftereffects in Visual Perception") are respectively assistant professor of psychology at the University of Montreal and professor of psychology at McGill University. Favreau was born and educated in Montreal and earned her Ph.D. at McGill in 1973. She joined the faculty at Montreal in 1974. Her work in visual perception grew out of her interests in psychology and in the visual arts. She is also concerned with the position of women in society, which has led her to look into research on differences in abilities according to sex. She has just completed a one-year term as a member of the Canadian Psychological Association's Task Force on the Status of Women in Psychology, where she did a survey of bias in research on sex differences. Corballis was born in New Zealand but is now a Canadian citizen. After being graduated from Victoria University College in New Zealand in 1959 with a master's degree in mathematics he switched to psychology, obtaining a master's in 1962 from the University of Auckland. Three years later he received his Ph.D. in psychology from McGill. After a brief period as a lecturer in psychology at Auckland he returned to McGill as a member of the faculty. Corballis is interested in most aspects of human experimental psychology, and this year he and Ivan L. Beale published a book titled *The Psychology of Left and Right.* He writes: "My wife and I both make stoneware pottery, she with greater expertise than I, and I can beat Olga Favreau at squash."

N. DAVID MERMIN and DAVID M. LEE ("Superfluid Helium 3") are professors of physics at Cornell University. Mermin received his bachelor's degree in mathematics from Harvard University in 1956 and remained there to get his Ph.D. in physics in 1961. He has been on the faculty at Cornell since 1964, working in the theoretical physics of condensed matter. He is the author of the nontechnical book *Space and Time in Special Relativity* and is coauthor (with N. W. Ashcroft) of a basic introductory text, *Solid State Physics.* Lee received his bachelor's degree in physics from Harvard in 1952. After a short period of military service he resumed his studies in physics, receiving a master's degree at the University of Connecticut in 1955 and a Ph.D. from Yale University in 1959. Since that time he has been a member of the faculty at Cornell. As a codiscoverer of the new superfluid phases of liquid helium 3, he has been awarded the Simon Prize by the British Institute of Physics (together with his colleagues Robert C. Richardson of Cornell and Douglas D. Osheroff, who is now at Bell Laboratories).

KEIR PEARSON ("The Control of Walking") is associate professor of physiology at the University of Alberta. Born in Tasmania, he received his undergraduate degree in electrical engineering from the University of Tasmania in 1964. In that year he received a Rhodes Scholarship that enabled him to pursue his studies at the University of Oxford. "I began research on micro-

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The SR-52 puts computer-like power to work and makes number tasks more manageable than ever before.

Optimization. Mathematical modeling. Iteration. Data reduction. Projections. What-if matrices. Risk analysis. Forecasts. Worst case analysis. Probability. If you're a professional—or studying to be one—then chances are you're making calculations like these. If you have the time, you work them out. Or, you get in line for computer time, then wait. So, more often than you'd like to admit, you rely on your intuition or make an educated guess. But you don't need to guess. You can know. Because programmables help you cope with more data, explore with more insight, far more successfully than ever before. You make better decisions, chosen from more options—better decisions founded on a broader data base. More decisions. Faster. On the spot.

Programming is just logical thinking. You can do it. You'll be writing programs in just a few hours. More than likely you won't be able to write optimum programs straight-off. (Programs which run the fastest and use the fewest steps.) However, you can begin writing programs that work. Then, record your program on a blank magnetic card and make it part of your personal library to use again and again.

You can process data or perform complex calculations automatically. Load the card and put its contents into program memory. Key variables directly into the program—or into the 20 data memory registers (up to 60 in certain cases). Run a program as often as needed. Change values of variables as often as you desire.

Program memory and data registers in abundance. Data recording, too. The SR-52's 224-step program memory uses merged prefixes, so each step can hold two keystrokes. With this capability, the SR-52 can handle programs you may have thought required a computer. Although the basic 20 data registers are usually more than adequate, you can use up to 40 additional registers. (28 in program memory, the 10 pending operations registers, and 2 more.) And you can record up to 28 data registers onto blank magnetic cards. Read them back later.

Computer-like branching. The SR-52 offers seven types of unconditional branching. And 10 conditional branches each with three ways to address: absolute, label, or indirect. That's 37 different branching instructions. Five flags can be set, cleared, or tested from the keyboard or within a program. You also get 10 user-defined keys.

Direct or indirect access to *all* data memories. Store numbers directly in any memory register. Or, store a number in a data memory specified by any other register (indirect addressing). Add, subtract, multiply, divide directly within all registers. Exchange display with memory.

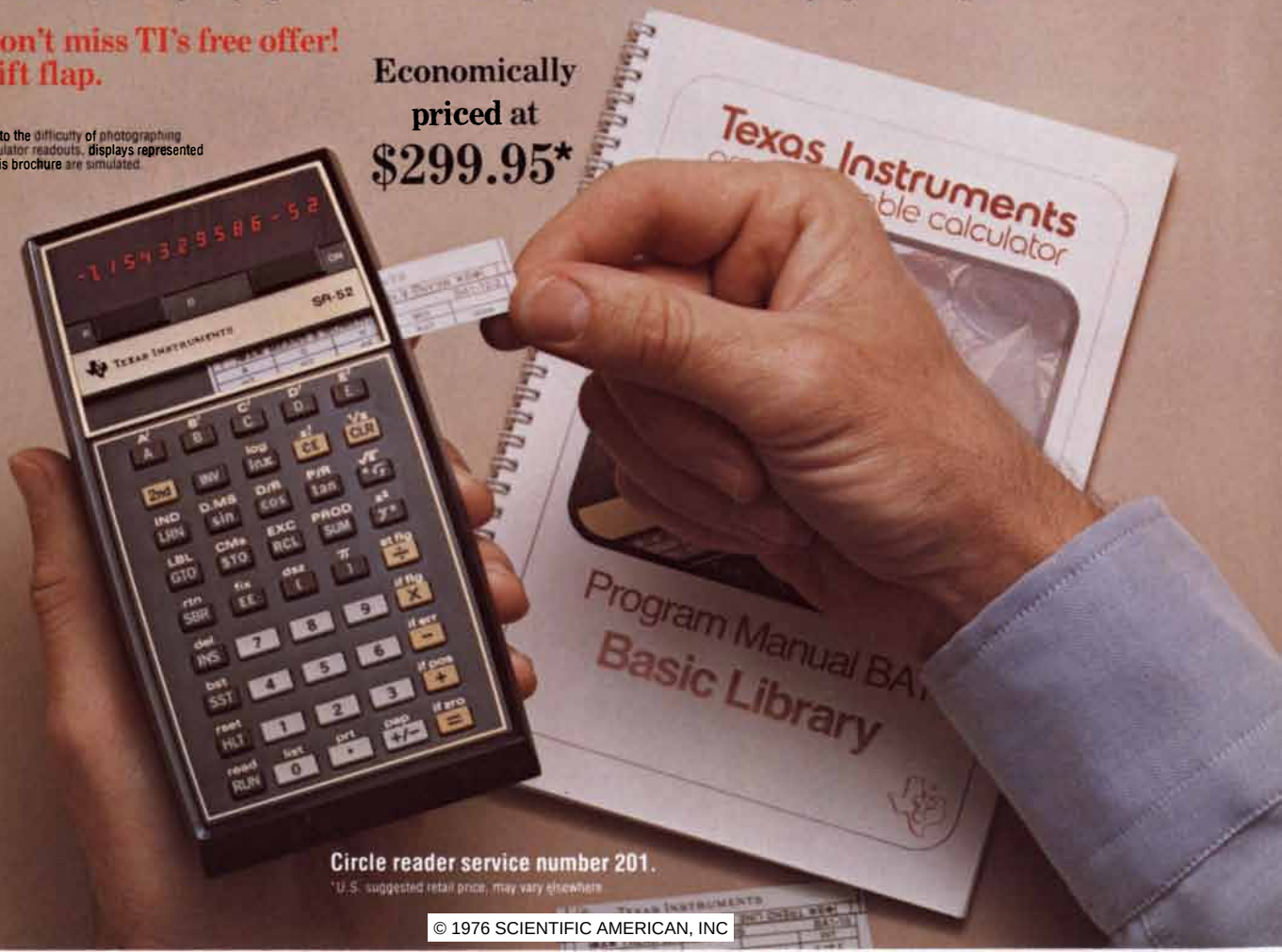
Edit and debug. Move through a program a step at a time. Forward or backward. Insert. Delete. Or write over steps. List and trace your programs on the PC-100 printer, an optional accessory.

Basic Library of 22 prerecorded programs included. Put them to work right away: math, statistics, finance, electrical engineering, and others. You also get a 96-page Basic Library manual. Supporting each prerecorded program card are sample problems, user instructions and program listings.

Don't miss TI's free offer! Lift flap.

Economically priced at $299.95*

Due to the difficulty of photographing calculator readouts, displays represented in this brochure are simulated.



Circle reader service number 201.

*U.S. suggested retail price, may vary elsewhere

SR-56. A double duty powerhouse. Incredible calculating capability... and you can program it too.

74-preprogrammed operations. Ten memories. Computer-like programmability in 100 steps. And it works with TI's PC-100 printer.

An eight-register stack (handles up to seven pending operations). You also get nine sets of parentheses.

Branches like a computer. Capable of direct addressing, which includes: Go to. Reset. Subroutine (4 levels). Plus six conditional branches.

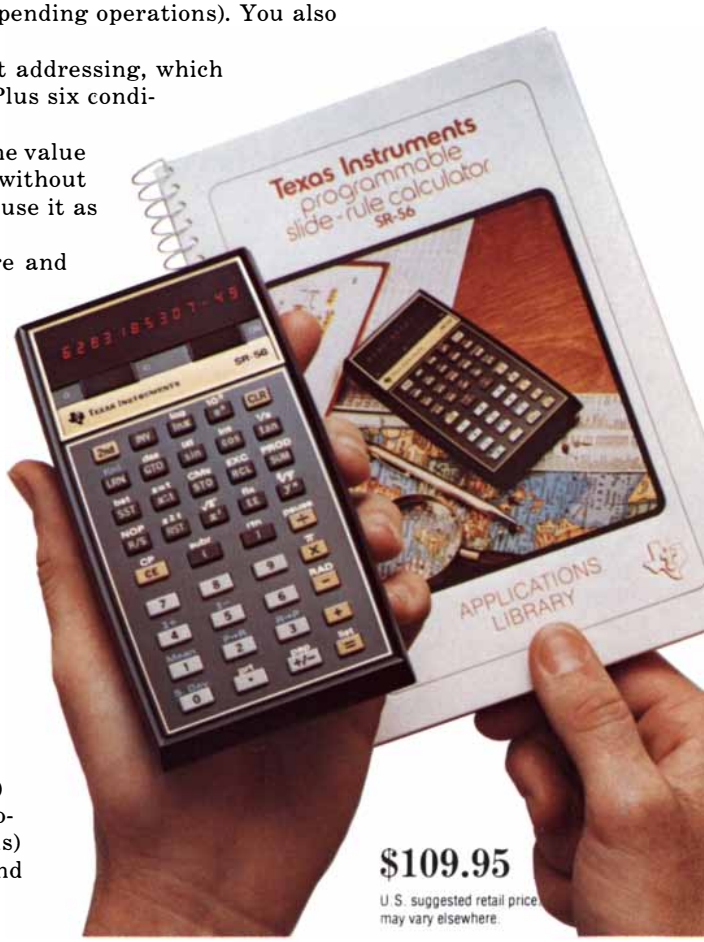
Unique independent test register. Compare the value in the display with a value in the t-register—without interfering with calculations in progress. Or, use it as an extra memory.

10 memories for your tough problems. Store and recall data. Add, subtract, multiply, or divide within a memory register without affecting the calculation in progress.

Unique pause key works two ways. Using this key in a program displays any step you designate for a ½-second. Hold the key down and you'll see the result of every step in the program for ½-second.

Easy editing. Single-step and back-step keys let you sequence through program memory to examine what you've done. If you pressed a key incorrectly, you can go back and write over it.

An applications library, too. A 192-page collection of programs. All pre-written. Select a program. Follow the listing (putting in your own data, of course). And you'll immediately begin using your SR-56's computing power to solve your own problems. • Math (10 programs) • Statistics (12 programs) • Finance (11 programs) • Electrical Engineering (11 programs) • Navigation (7 programs) • Miscellaneous and games (5 programs.)



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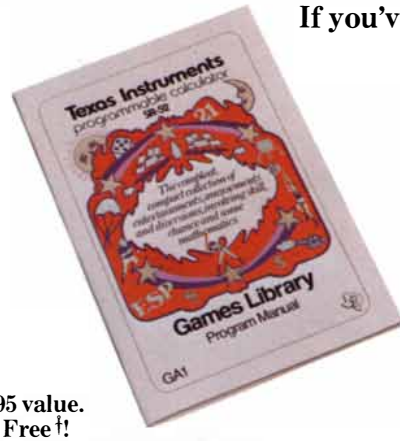

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Brain Teasers: Number Guesser. Hi-Lo. Interchange. Code Breaker. Star Buster.

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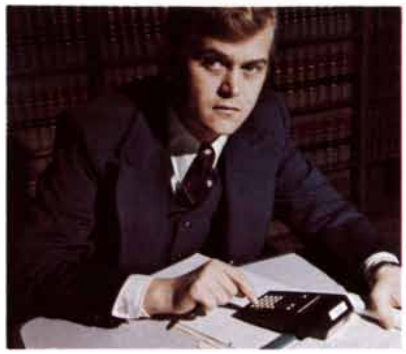
Good value judgements help professionals succeed. Choosing an SR-52 is an important example. Because it helps professionals make better decisions. Anytime. Anywhere.

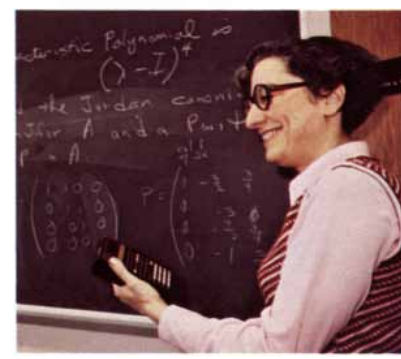


Law. "The court here handles about a million cases a year on the misdemeanor level – traffic and minor offenses. We're trying to improve our efficiency so we've been collecting statistical data: How many cases are we getting? What kinds? What happens to them? My SR-52 is helping me analyze these statistics. Its value is going to continually grow in importance as this data base increases. With a better handle on case load, dispositions, follow-up – my administrative skills will improve."
Joseph A. Tvedt,
Attorney, City
Prosecutor's Office,
Phoenix, Arizona

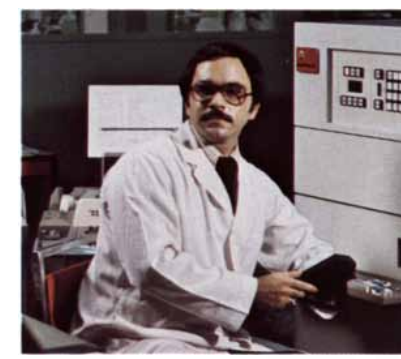
Surveying. "We make a lot of oil field surveys. Onshore and offshore. We use SR-52's because our crew chiefs in the field don't have to call the office for calculations. They run the program right on the spot. That's especially useful at sea when you've got 50 to 100 calculations to make. Like when a big oil rig is moved. Our bread and butter program determines position, direction and distance to the point it has to reach. It calculates it for us within two to three seconds. We also have a PC-100 in the office."
Howard Fenstermaker,
Civil Engineer/Surveyor,
C. H. Fenstermaker and Associates,
Lafayette, Louisiana

Mechanical Engineering. "Our products are sub-fractional horsepower gear motors. Several gear stress calculations go into every motor design. It takes one to three hours of hand calculations to optimize a gear train design. So I decided to program the problem on an SR-52. Now it takes less than 30 minutes. Design engineers use it too. These programs give our engineers the time to make the calculations, adding analytic assurance to their experience. And it ensures having a good gear motor design the first time around."
Steven Hollander,
Assistant Vice President,
Molon Motor and Coil Corp.
Rolling Meadows, Illinois

Insurance. "Part of my work is checking the reasonable relationship between the value given and the premium charged on insurance. I like the capability of storing factors on a mag card. It eliminates having to go back and forth between books of actuarial tables and my program. It's convenient. Efficient. I take it to my meetings. So I can run a program right on the spot. The '52 Owners Manual is excellent, too. Like reading a good detective story. So in a couple of weeks I got pretty darn good at programming."
Edward A. Flickner, Jr.
Life Actuary,
The State of Georgia,
Atlanta, Georgia



Mathematics. "The two programs that I submitted to PPX-52 – your Professional Program Exchange – involve matrices: multiplication, inversion and determinant. It's error-prone to do these by hand, while using a computer is expensive and bothersome. The SR-52's looping and indirect addressing features are essential to my matrix problems. I sometimes use my SR-52 to show students what they can expect from larger computers in a way they understand."
Barbara Osofsky,
Professor of Mathematics
Rutgers University,
New Brunswick, New Jersey



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Memories	10	22
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Sum/Subt to Memory	●	●
Mult/Div to Memory	●	●
Exchange display with memory	●	●
Additional special memories	1	38
Indirect memory addressing	–	●
Exchange x with t	●	–
Fixed decimal option	●	●
Calculating digits	12	12
Angular mode Deg/Rad	●	●
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Digits displayed (mantissa + exponent)	10 + 2	10 + 2

Calculating characteristics	SR-56	SR-52
Log, lnx	●	●
10^x, e^x	●	●
x^2, $\sqrt{X}$	●	●
1/X, π	●	●
Y^x	●	●
$\sqrt[x]{y}$	●	●
X!	●*	●
Int X (integer part)	●	●*
Fractional part	●	●*
Trig functions & inverses	●	●
Hyperbolic functions & inverses	●*	●*
Deg/min/sec to decimal deg & inverse	●*	●
Deg to Rad conversion & inverse	●*	●
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Program read/write on mag. cards	–	●
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User defined keys	–	10
Possible labels	–	72
Absolute addressing	●	●
Subroutine levels	4	2
Program flags	–	5
Decrement & skip on zero (loop)	●	●
Conditional branching instructions	6	30
Unconditional branching	3	7
Indirect branching	–	●
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NOP	●	–
Single step execution	●	●
Pause	●	–

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wave-semiconductor interactions," he recounts, "but very quickly lost interest in that type of research. Then through a series of lucky events I was introduced to the fascinating field of invertebrate neurophysiology, and to the analysis of the electrical events in single nerve cells and small systems of nerve cells." He changed fields and completed his doctorate in neurophysiology in 1968. From 1967 to 1969 he was a junior research fellow at Merton College, Oxford. He moved to Canada and joined the department of physiology at the University of Alberta in 1969.

ROBERT P. KIRSHNER ("Supernovas in Other Galaxies") is assistant professor of astronomy at the University of Michigan. He went to Michigan in September after two years as a postdoctoral fellow at the Kitt Peak National Observatory in Arizona. During that time he worked on problems related to supernovas and supernova remnants, on the dynamics of groups of galaxies and on the luminosity of galaxies with respect to their distance. He went to Kitt Peak in 1974 after receiving his Ph.D. from the California Institute of Technology, where he had gone in 1970 after being graduated from Harvard University. His article was written while he was at the Aspen Center for Physics.

ALLAN M. CAMPBELL ("How Viruses Insert Their DNA into the DNA of the Host Cell") is professor of biological sciences at Stanford University. He received his Ph.D. from the University of Illinois in 1953 and then was appointed instructor in bacteriology at the University of Michigan. In 1958 he went to the University of Rochester, where he became professor of biology; he moved to Stanford in 1968. In 1971 he was elected to the National Academy of Sciences and to the American Academy of Arts and Sciences. His research interests have all been in the area of microbial genetics, although they have not been confined to the particular problem of virus insertion.

J. D. MACDOUGALL ("Fission-Track Dating") is assistant professor in the Geological Research Division of the Scripps Institution of Oceanography at the University of California at San Diego. Born in Toronto, he obtained his bachelor's degree in geology at the University of Toronto in 1967. A year later he completed a master's degree at McMaster University by conducting a geochemical study in the Canadian Arctic Islands and then went to Scripps. After completing his Ph.D. in the earth sciences he spent six months as a visiting fellow in geophysics at the Tata Institute of Fundamental Research in Bombay and two years at the University of California at Berkeley. He returned to Scripps in 1974.

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The Pluralistic Economy of the U.S.

One worker in three is employed in the not-for-profit sector. This fact calls into question some traditional conceptions of the economy and suggests new approaches to gaining a fuller understanding of it

by Eli Ginzberg

The nation has been through another quadrennial election campaign in which voters were exhorted to preserve (or strengthen or revitalize or more equally distribute the fruits of) our private-enterprise system. Few truisms are so firmly implanted in the American consciousness as the notion that our economy is a private-enterprise one. The fact is that it is not. It is private and public, profit-making and not-for-profit: a pluralistic economy of private enterprise, nonprofit institutions and government. Persistent failure to recognize this pluralism and to perceive the interrelations of the economy's various elements clouds understanding of important economic issues and makes it harder to deal with some current problems.

More than 10 years ago Dale L. Hiestand, Beatrice G. Reubens and I became convinced that the dominant picture of the U.S. economy as a private-enterprise system was in need of revision. Even before we looked closely at the figures we surmised that the cumulative growth of government—national, state and local—had permanently altered the structure and functioning of the economy, and that the economy could no longer be encapsulated within a private-enterprise, profit-maximizing model. The main effort of our inquiry was to find the answer to one critical question: What proportion of the U.S. economy's output and employment was accounted for by activities outside the private, profit-oriented sector? Our considered answer was that about a fourth of the gross national product and no less than a third (and possibly as much as two-fifths) of the country's employment was generated by nonprofit institutions and government, which is to say by the not-for-profit sector.

One might have expected such a finding, published in 1965 in our book *The Pluralistic Economy,* to attract attention. It did, but primarily abroad; it was largely ignored by economists and journalists at home. Foreign observers in both developed and developing countries had no difficulty absorbing the evidence of the rapid growth of the not-for-profit sector in the U.S. economy. They knew that their own governments played a dominant role in shaping their economies, and they had no reason to question the finding that government had come to play a critical role in this country too. Our colleagues at home preferred to ignore our findings rather than confronting them. Conservatives and liberals alike were comfortable with the old view that the private sector continued to dominate the American economy, the one group applauding and the other group criticizing that basic state of affairs. It was less disturbing intellectually and less threatening ideologically (regardless of the particular ideology) to reaffirm the conventional wisdom that the economy operates under market forces, with government's role limited to adjustments of the rules of the game and the distribution of rewards.

Little has changed in the decade since our book was published. Presidents Johnson, Nixon and Ford—and many other people—have continued to emphasize that "five out of six jobs" are based in the private sector, as if repetition and emphasis could alter arithmetic. What are the facts? Hiestand recently brought our 1963 data up to 1973. With total national employment in that year at 84.7 million, "general government" employees came to 13.4 million (full-time-equivalent workers). That is the basis for the five-out-of-six reference. It makes no sense, however, to isolate direct government employment and call everything else private. The important distinction is between the private, profit-seeking sector and the total not-for-profit sector.

To begin with, the private sector is not all that private. When the Federal Government buys missiles from Lockheed or naval vessels from Litton, workers employed in those companies' West Coast plants or Gulf Coast shipyards are classified as employees of the private-enterprise sector, but no economist should be comfortable with such a designation. The wages those workers earn are paid for out of Federal Government funds, and their output is absorbed exclusively by the Government. For years the Army has manufactured some of its ammunition in its own arsenals, whose workers have always been counted as Government employees. It is hard to see the logic of classifying those who work for defense contractors as belonging in the private sector any more than the arsenal workers belong in it, since their output is absorbed by government.

This principle of classification extends far beyond defense. In seeking to draw realistic boundaries between the private and the not-for-profit sectors we believe all employment generated by government purchases of all kinds in the private sector must be counted as part of the not-for-profit sector. This can be done by converting the dollars government spends on such purchases into

an equivalent employment figure. Hiestand's calculations for 1973 show government purchases from the private sector as amounting to 9.9 percent of the gross national product. He calculates that this represents 8.4 percent of the total employment of 84.7 million, or 7.1 million workers. The combined direct and indirect employment of all government in 1973, then, was 13.4 million plus 7.1 million, or 20.5 million. About one American worker in four depends for his job on the activities of government, directly or indirectly.

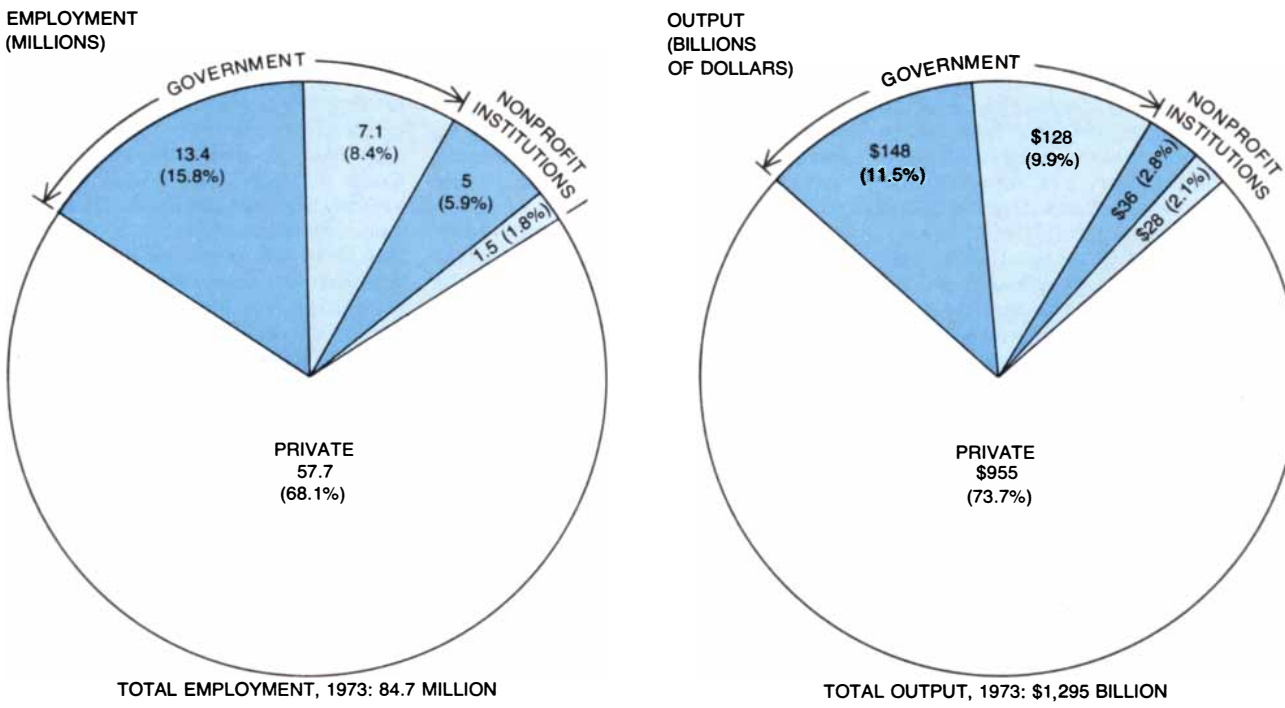
Although government is the largest component of the not-for-profit sector, it is not the only one. The other significant segment comprises the nonprofit institutions: churches, colleges, voluntary hospitals, labor unions, social organizations, special-interest associations and many more. Hiestand's calculations for 1973 show a total direct employment of five million in these nonprofit institutions, or 5.9 percent of total employment. Here as in the case of government, however, one must take into account the purchases by nonprofit institutions from the private sector in order to obtain a total view of the economic impact of those institutions. Converting the purchases into employment adds another 1.8 percent, giving the nonprofit institutions a total of 7.7 percent of U.S. employment.

We are now in a position to derive a more realistic estimate of the role played by the entire not-for-profit sector in terms of employment. Government is responsible for 24.2 percent of U.S. employment and nonprofit institutions for 7.7; the two add up to 31.9 percent. It would be desirable to add to that a small increment reflecting government or quasi-governmental employees in, for example, the Postal Service, municipal hospital systems and state liquor stores. Those figures are obscured, however, because we are converting dollars of purchases into employment, and the Department of Commerce includes such enterprises not in the government sector but in the business sector of its national-income accounts! Even if they represent only a percent or two of total employment, it is clear that the not-for-profit sector as a whole is responsible for one out of three, rather than one out of six, American workers. A complementary picture in terms of dollars can be developed by calculating the total output of goods and services accounted for by government and nonprofit institutions as a proportion of the gross national product [*see illustration below*]. The larger role of the not-for-profit sector in employment than in gross national product reflects two factors: a larger proportion of that sector's total expenditures goes to payrolls and below-average wages are paid by nonprofit institutions.

The weight of this evidence is unequivocal. The American economy is much less private than either its defenders or its critics have assumed. Moreover, one should note that government transfer payments to or on behalf of individuals, such as food stamps or Medicaid payments to private nursing homes, are not included in national-income accounts. Such transfers would add another 3 to 5 percent to the not-for-profit sector's share of output and of equivalent employment.

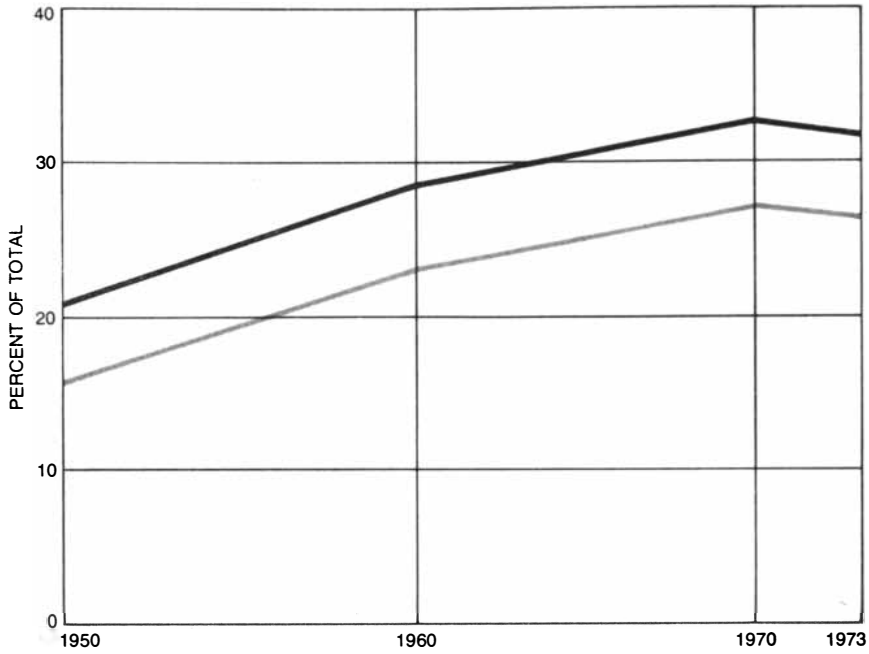
A second critical question relates to the trend. Conservatives call for action to halt the rapid rise in government spending, which they consider to be the road to inflation and ruin. Through recourse to linear extrapolation they insist that unless the trend is broken it will not be long until government controls most of the country's resources and output. (In the countries of Western Europe, on the other hand, there has been much less concern about the growth of the government sector, at least until recently.) Hiestand has looked at the U.S. trend since 1929. In that year the not-for-profit sector accounted for about 15 percent of total employment and 12.5 percent of output. In terms of either measure, employment or share of the gross national product, the increase through the Depression years and World War II was gradual; the most striking advance for the not-for-profit sector came in the 1950's. There was some additional growth in the 1960's, but it was much slower. And in the early years of this decade there was a slight decline.

The analysis up to this point has assumed that there is a clear-cut differentiation between the private profit-seeking



NOT-FOR-PROFIT SECTOR of the U.S. economy (*color*) is composed of Federal, state and local governments and nonprofit institutions. In terms of both employment (*left*) and output, or gross national product (*right*), the not-for-profit sector has both a direct role (*dark color*) and an indirect role (*light color*). The direct role is measured in terms of the direct employment and payrolls of governments and nonprofit institutions; the indirect role is played by their purchases from nominally private enterprises and by the equivalent indirect employment. The total share of the not-for-profit sector is 31.9 percent of employment and 26.3 percent of the gross national product.

sector and the not-for-profit one. A more sensitive delineation of the boundaries of the profit-seeking arena would have to take note of the fact that several of the nation's largest industries operate under government controls that constrict their freedom with respect to both prices and profits. At a minimum one would have to consider as something less than completely private those enterprises engaged in transportation, communications and the production of power. In 1974 they accounted for approximately 4.7 million employees, or about 5 percent of the total employment, and they contributed 11 percent of the total gross national product. There is no point in exploiting the data further to expand the "controlled" sector, except perhaps to note that three additional industries—agriculture, banking and insurance—operate at least in part under price and profit controls.



GROWTH OF NOT-FOR-PROFIT SECTOR has not been at a steady rate. The most striking advance in share of employment (*black curve*) and of gross national product (*gray curve*) was in the 1950's. Between 1970 and 1973 there was a small decrease in the sector's share.

The heated political debate on the relative sizes of the private sector and the public one is frequently conducted with such slogans as "the market" v. "economic planning" or, in their more extreme form, "capitalism" v. "socialism." Less emotionally charged terms are more appropriate. Potent factors have been operating to enlarge the not-for-profit sector. Among the most important has been the much enlarged role of the Federal Government since World War II in defense and in defense-related areas such as space, atomic energy and a broad range of research-and-development activities. More recently the expanding Federal commitment in education, manpower and health has also been a potent factor.

Yet the fastest-growing sector of government, particularly in terms of employment, has not been the Federal Government at all but state and local government. These jurisdictions were forced to respond to the demands of an expanding population for improved services in such fields as education, health and welfare and for such conventional services as police and fire protection and sanitation. In terms of personnel, state and local governments have been the most rapidly expanding sector of the American economy. In 1950 their total employment was 4.3 million; in 1974 it came to 11.8 million, an increase of 174 percent. Total employment in the same period increased by only 46 percent. Many of the same forces that stimulated the growth of government were also responsible for the relatively rapid growth of nonprofit institutions, particularly in higher education and hospitals.

Those who see the growth of the not-for-profit sector primarily as an ideological issue fail to appreciate the extent to which it reflects the inability of the private sector to respond to priority needs and desires of the American people. One can argue about whether or not the U.S. overreacted to the threat of Russian expansion, but once the threat was defined as being serious it was inevitable that the nation's defense and defense-related expenditures would increase. Similarly, ideology has had very little to do with the desire of the public for improved access to higher education and health services. It took many years for the health reformers to overcome the opposition of the American Medical Association, but the eventual passage of Medicare in 1965 was effected by broad-based political support.

Once the American people had made choices for strong defense, more access to higher education and improved medical care, the die was cast in favor of an enlarged role for the not-for-profit sector. Moreover, there was no way for the nation to accommodate its rapidly rising population and the irrepressible demand for a suburban way of life unless all levels of government expanded. The growth of the not-for-profit sector was inevitable because the goods and services that a more affluent America wanted could not be provided by private-sector entrepreneurs operating through the market. Important as the private sector has been in stimulating the growth of the economy, there is no way to read our recent history without recognizing the strategic part government and nonprofit institutions have played in providing new entrepreneurial structures for meeting new needs and desires of the public.

The focus on defense, education and health provides a background to one of the most important economic transformations now under way: the growth of the service economy. The full details and implications of this transformation have still not been adequately examined or assessed. One simple way to gauge its scale is to compare the four goods-producing industries—agriculture, mining, manufacturing and construction—with all other activities, which are conventionally grouped under the heading of services [*see illustration on next page*].

Almost the entire growth in post–World War II employment has been in the service sector. Among the goods-producing industries only construction shows any sizable increase. Agriculture declined by more than half, from some 7.6 to 3.5 million; mining declined by approximately a third, from 955,000 to 672,000; manufacturing—the backbone of the economy—showed only a small absolute increase: approximately a third, from 15.6 to 20 million, which meant that its share of total employment dropped from about 27 percent to 21 percent. In terms of contribution to the gross national product the relative decline of the goods-producing sector was less steep. Between 1950 and 1974 manufacturing actually registered a small increase in its share of output: in 1950 that share was 29.7 percent and in 1974 it was 30.8 percent.

The rapid growth of services and their newly acquired dominance in the expansion of employment, along with the bias toward commodity transactions that is inherent in economic analysis, guarantee that many efforts to diagnose economic ills and to devise new programs are doomed to error and frustration. A few illustrations will make this clear.

There has recently been much com-

ment in Washington and among captains of industry about a disastrous decline in the productivity of the American economy and the danger such a decline presents to our international competitive position and our long-run economic well-being. People have also sought to explain the fact that our rate of growth is slower than, say, Japan's by arguing that we devote too much of our income to consumption and too little to saving and investment. That we save and invest proportionately less than Japan is true, but the productivity-growth argument has a further dimension that is related to the size of the government sector in the two countries. By convention the output of the larger U.S. government sector is measured in terms of the inputs: the dollars spent for payrolls and other purposes, which are assumed to equal the value of the services provided. Hence there is no way for this large sector to contribute to an increase in total productivity. National-income accounting practices force the much-reduced private sector to carry the entire burden of registering productivity gains.

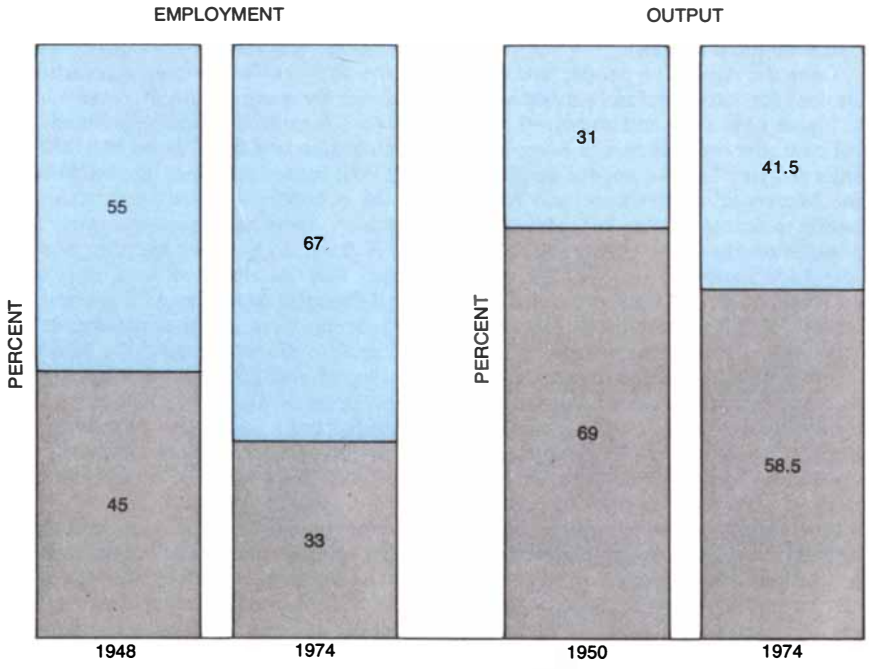
The difficulties run deeper than that, however. The key to service output is quality, not quantity. For example, before there were antibiotics people with severe infections often died and others required weeks or months of care before they recovered. Today such patients are often cured within a few days by one injection or a series of them. The national-income accounts do not reflect the improved quality of medical care or of other services. We measure the gains in productivity in the manufacture of television sets but assume that the quality of programming remains the same.

The burden of these few illustrations is to argue the case that the shift from goods production to services, a cause and a concomitant of the growth of the not-for-profit sector, has fundamentally distorted our system of national accounts, has complicated our ability to locate points of weakness in our economic system and has compounded the difficulties of designing effective solutions.

We are still at an early stage in our ability to differentiate among the component parts of the service sector, which in 1974 accounted for two-thirds of total employment and $534 billion of output. People tend to think in terms of consumer services, from medical care to hairdressing. There has also been large growth in the producer services: the services, such as trucking, advertising, law, management consulting and computing and all the rest, that support the profit-making activities of the business sector. It is surprising that Harry I. Greenfield's 1967 book *Manpower and the Growth of Producer Services* was the first serious consideration of the role of those important services in economic development. My colleagues and I in our ongoing studies of New York City (which is overwhelmingly a service economy, with more than 80 percent of total employment in the service sector) stress that the city's future depends less on attracting back some of the manufacturing firms that have left it than it does on retaining and strengthening its complex of corporate headquarters and the advanced services—banking, legal, accounting, communications, public relations—that are linked together and mutually support one another and the corporate headquarters.

It is no sign of disrespect to point out in this bicentennial year of the publication of Adam Smith's *The Wealth of Nations* that economists, politicians and journalists are caught up in a Smithian fallacy. Smith argued that the test of productive labor was whether the work resulted in material output: a physical representation of the time and effort expended. In short, the craftsman who builds a violin is productive but Heifetz and Menuhin are not; the manufacturer of a scalpel is productive, but not the surgeon who excises a tumor and thereby saves a life.

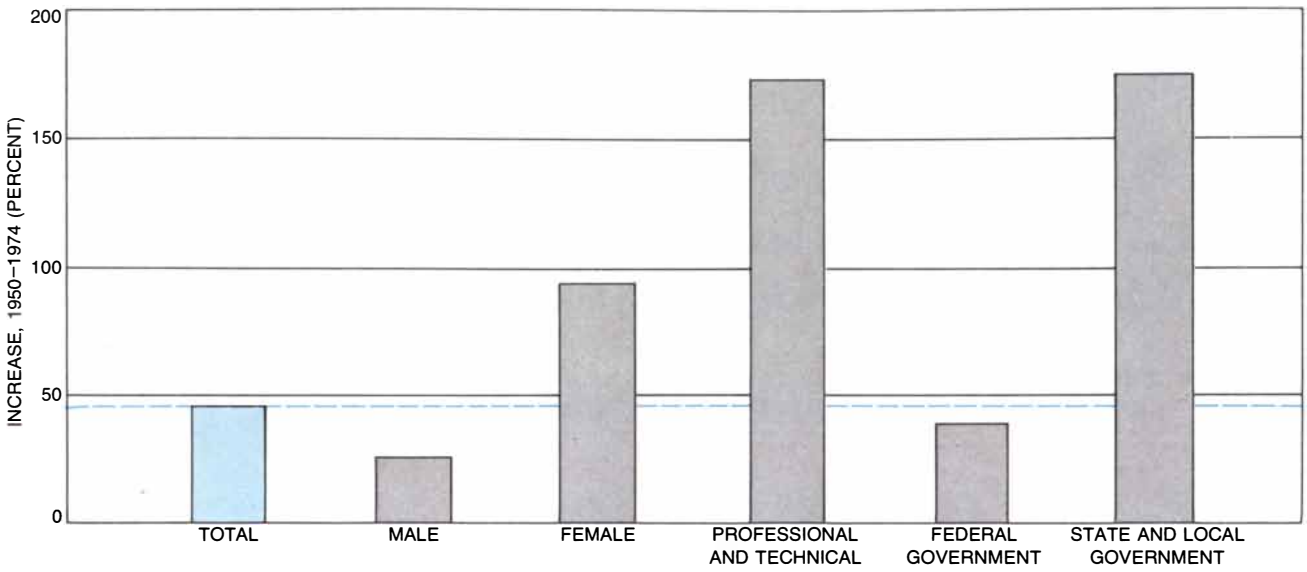
Smith wanted to emphasize an important point. He was concerned by the fact that, as he saw it, a great many people were being "kept." He included the extraordinarily large number of household retainers, bureaucrats whose sole activity was to get in the way of ambitious businessmen, members of the court and other supernumeraries. In Smith's view such people contributed nothing to the growth of the economy. Today only a dyed-in-the-wool Keynesian (who would prefer to have government pay men to dig holes than to have them idle) would challenge him. In striving after the distinction between productive and unproductive labor, however, Smith pressed too hard and went too far. And many who came after him absorbed his prejudice without appreciating the particular distinction he was trying to make.



SHIFT TO SERVICES accompanied the growth of the not-for-profit sector. The share of the goods-producing industries (agriculture, mining, manufacturing and construction) in total employment (*left*) and output (*right*) decreased over a quarter of a century (*gray*). The share of the services (trade, government, transportation, utilities, finance and others) increased (*color*).

There have been several important manpower concomitants to the rapid growth of the not-for-profit and service sectors of the economy. The services have facilitated the rapid growth of female employment. Between 1950 and 1974 the civilian employment of males 16 years and over increased from 41.6 to 52.5 million, or by approximately 26 percent. During the same period the number of female workers employed increased from 17.3 to 33.4 million, or by 93 percent: three and a half times as much.

Not only did the number of new job openings available to women increase but also the services were more able to offer less-than-full-time employment, a schedule of work that both the employers and many women preferred. This accommodation was not all gain, to be sure: it meant that many women workers were not able to obtain desirable full-time jobs with fringe benefits, security and opportunity for career development. Whereas many women found what they wanted—work that was not too demanding and gave them an opportunity to supplement their family in-



SHIFTS IN EMPLOYMENT reflect the enlargement of the not-for-profit sector, in which services predominate. Here the increases in employment from 1950 to 1974 are given for several categories. Whereas total employment increased 46 percent in that time, male employment rose less than that and female employment rose more. The shift to services brought a large increase in professional and technical jobs. Federal Government jobs increased less than total employment, whereas employment by state and local governments soared.

come and to get out of the home—many others who were the head of a family or who had strong career drives were hard-pressed to find suitable job and career openings.

The rapid expansion of service employment also opened up many opportunities for part-time or intermittent work for young people whose main activity was pursuing their education. The period after World War II witnessed a rapid expansion in postsecondary education supported in no small measure by the enlarged earning opportunities that were opened up for students in a broad array of service industries.

One of the striking consequences of the increase in the proportion of women and of students employed and in the labor force was the extent to which the prototype of a worker as a person employed full time for the full year from young adulthood until retirement no longer fits the American scene. As Dean Morse pointed out some years ago in *The Peripheral Worker,* of all people who work during the course of a year almost 45 percent are employed less than full time for the full year; only 55 percent fit the stereotype of the conventional worker. Even if the calculation is shifted from the number of workers to the total work performed, one finds that about 30 percent of all work is performed by those who are not full-time workers.

Another important manpower concomitant of the recent expansion of services has been the substantial growth of professionals, in education, health, management, science, engineering and many other fields. For two and a half decades, from 1945 to 1970, the economy was able to absorb the increasing output of the colleges, graduate schools and professional schools with no serious evidence of any weakening in demand. In part this balance reflected the relatively long time required to expand the structure of higher education and to fill the pipeline. In part it reflected the enlarged expenditures by government for research and development, which created a new market that absorbed many of the newly trained specialists. By 1970, however, the supply had overtaken the demand, and since then the outlook for educated manpower has appreciably worsened, particularly for people with degrees in the humanities.

In my view there is a strong linkage among the following: the growth of the not-for-profit sector, the substantial increase in educated manpower, the rapid growth of the advanced services and the generally good record of performance of the American economy. To the extent that these developments are interrelated—and it is difficult to see how they could not be—we find confirmation for the basic thesis on which the pluralistic economy of the U.S. is based. It is not simply the growth of the not-for-profit sector that is critical. It is rather the new articulations between the not-for-profit sector and the private sector based on the principle of complementarity. The prosperity of the automotive industry has long depended on an expanding national highway system. Similarly, the argument can be made, the research-based and science-based industries and advanced services that continue to provide the frontiers of the economy—from more powerful computers to strengthened capital markets—depend on the trained manpower produced in the colleges and universities based in the not-for-profit sector. To discuss the not-for-profit sector as a profligate spender of scarce resources without reference to its critical contribution to enlarging the wealth and welfare of the American economy and society may arouse enthusiasm among certain components of the body politic, but it is not likely to win much favor or have much influence on public policy, even among a people that considers its tax burden onerous.

A society can act more intelligently if it has a clearer perception of the nature and functioning of its basic institutions. This article has sought to provide a few modest clarifications, which I shall summarize.

The U.S. economy, while still dependent on a large and vigorous private sector, is in fact a pluralistic economy in which the not-for-profit sector accounts for one in every three jobs.

With the goods-producing industries accounting for an ever smaller part of the nation's output and employment, it is critically important that we abandon simplistic reliance on a manufacturing model and deepen our understanding of the role of services in the production of wealth and welfare. For example, concern about the slow growth of productivity may or may not be justified, but nobody really knows whether it is because we have not learned how to measure productivity in the services.

The foundation for an advanced service economy is trained manpower. This manpower is educated in the not-for-profit sector, thereby establishing the principle of complementarity between it and the private sector and illustrating the interdependence of the various elements of our pluralistic economy.

The Reprocessing of Nuclear Fuels

The economics of fission power would be much improved if spent fuel were processed to remove fission products and plutonium and reclaim uranium. The industry needed for the task does not yet exist in the U.S.

by William P. Bebbington

Nineteen years after the first American nuclear power station went into service at Shippingport, Pa., the U.S. still has no commercial facility licensed to recover plutonium and unburned uranium 235 from the spent fuel of nuclear power reactors. Only one private plant was ever licensed to operate, and it was shut down in 1972 for modifications and enlargement. Its owners, Nuclear Fuel Services, Inc., of West Valley, N.Y., have since withdrawn their application for a license to reopen. Between 1966 and 1972 the plant reprocessed somewhat less than 650 tons of spent fuel. In Barnwell County, S.C., the separation facilities of a $500-million reprocessing plant with a capacity of 1,500 tons per year, owned by Allied-General Nuclear Services, were completed about a year ago. The owners are awaiting a Nuclear Regulatory Commission license, which in turn hinges on Government decisions on waste storage and on rules governing the utilization of recovered plutonium. Britain, France and several other countries reprocess spent fuel from nuclear power reactors in government facilities, but that is not the policy in the U.S. As a result the spent fuel from the nation's 62 operating fission power reactors has been piling up at repository sites. The current inventory is now about 2,500 metric tons.

Unlike coal, the fissionable fuel of a nuclear power reactor cannot be "burned" until all that is left is an essentially worthless and innocuous ash. The fresh fuel for American power reactors usually contains between 2.5 and 3.5 percent of the fissionable isotope uranium 235, having been enriched from the natural value of .7 percent uranium 235 by the gaseous-diffusion process. The remainder of the uranium in the fuel (and in the natural ore) is almost entirely the nonfissionable isotope uranium 238. When the nuclei of uranium 235 fission in the reactor, they give rise to a great variety of radioactive products, many of which act as fission "poisons" by absorbing the neutrons needed to keep the chain reaction going. By the time the uranium-235 content of the fuel has decreased to about 1 percent, the combined effects of depletion and by-product poisoning make it necessary to replace the fuel.

In addition to uranium 235 the spent fuel contains between .7 and 1 percent of plutonium 239, synthesized from uranium 238 by the absorption of a neutron. Plutonium 239 is even more fissionable than uranium 235, and the Federal Government is now deciding whether or not to approve the use of reactor fuel containing a mixture of the two nuclides. The fissionable material recovered from the spent fuel of three reactors is sufficient to fuel a fourth. The economics of the nuclear power industry will be strongly influenced by the decision that will allow or not allow the use of recycled, mixed fuels.

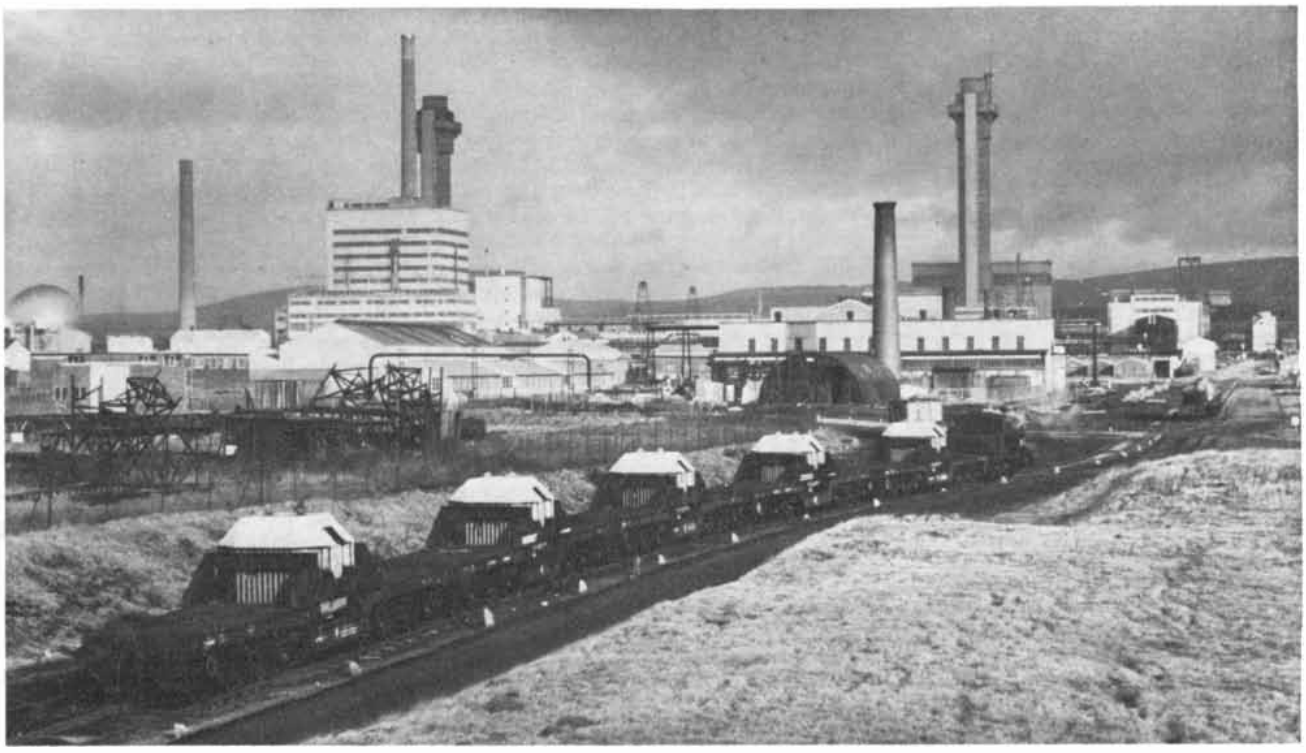
At the moment a reactor is shut down its spent fuel contains some 450 synthetically produced nuclides, including uranium 237 and neptunium 239, which decay into neptunium 237 and plutonium 239. The methods for chemically separating plutonium from uranium and its fission by-products were developed during World War II to provide highly purified plutonium for atomic bombs. Plutonium 239 was separated from the unenriched metallic uranium that served as the fuel of the Manhattan District reactors at Hanford, Wash. The heat from the reactors was discarded in the cooling water, and initially only the plutonium was recovered.

Uranium, neptunium and plutonium are members of the actinide series of elements, whose chemical properties are similar to those of the lanthanide series of rare-earth elements. Some months before Enrico Fermi and his coworkers demonstrated that plutonium could be made by a chain reaction in a uranium pile Glenn T. Seaborg and his colleagues had separated and purified several micrograms of pure plutonium metal that had been created by the bombardment of uranium in cyclotrons. The early studies revealed that plutonium had chemical properties that varied with its oxidation state and that could thus be exploited for separation processes. Those useful properties included the solubility of plutonium phosphates and fluorides in aqueous solutions (compared with the insolubility of the phosphates and fluorides of fission products) and the fact that certain plutonium ions could be extracted with organic solvents.

The fission products are isotopes of elements ranging in atomic number from 30 (zinc) to 66 (dysprosium). Most of them are radioactive, with half-lives that range from less than a second to thousands of years. The fission products are the chief source of the heat and radiation from spent fuel. Only a dozen or so combine intense radiation and long half-life with chemical and physical properties that are troublesome in reprocessing or in the ultimate disposal of wastes.

The first step in the treatment of spent nuclear fuel is to store it for several months in water-filled pools at the nuclear power station. During this period the radioactivity and the evolution of heat decrease by a factor of about 10,000. For example, the radioactivity of iodine 131, which has a half-life of 8.14 days, decreases by a factor of between 3,000 and 30,000. Indeed, iodine 131 is the chief determinant of how long the fuel is allowed to cool: the decay of the volatile element removes it as a problem in reprocessing.

The designers of the chemical separation plants at Hanford recognized that the technological innovations required for conducting chemical operations by remote control behind thick concrete walls were demanding enough without trying to achieve such niceties as the optimization of the process. They chose the simple batch operations that had been developed by Seaborg for working with microgram amounts of plutonium. Briefly, the uranium rods were first dissolved in acid, leaving an aqueous solution in which plutonium ions were extremely dilute. Bismuth and lanthanum were added as "carriers," so that when bismuth phosphate and lanthanum fluo-



WORLD'S LARGEST REPROCESSING PLANT for recovering uranium and plutonium from the spent fuels of nuclear power reactors is the Windscale plant at Seascale on the west coast of England. The facility was originally built to reprocess uranium from Britain's first plutonium-production reactors, which are barely visible in the distance. The multistory building with the tallest stack is the original plutonium-extraction facility. Its height was needed so that process streams of organic and aqueous solutions could flow countercurrently by gravity through extraction columns. The special railroad cars in the foreground are delivering spent nuclear fuel from power stations operated by the United Kingdom Central Electricity Generating Board. The Windscale plant, operated by British Nuclear Fuels Ltd., a government-owned corporation, can process 2,000 to 2,500 tons of fuel per year, and has processed fuels from several other nations.

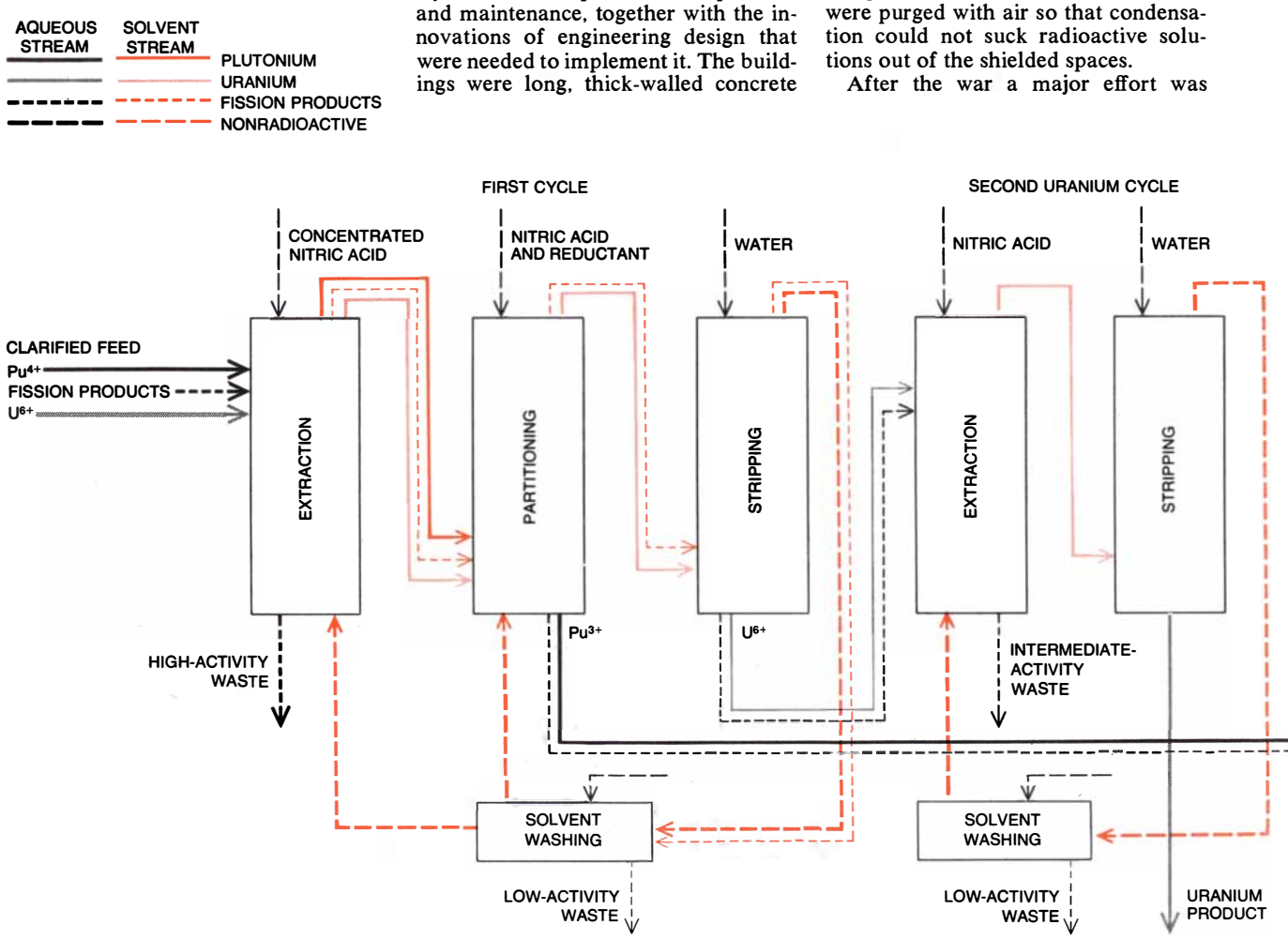
OPERATING FLOOR AT WINDSCALE supports rows of motors that turn the agitators of "mixer-settlers," multistage horizontal chambers that perform the same function as extraction columns in bringing organic and aqueous solutions into intimate contact (*see illustration on page 35*). The plant operators are shielded by a thick concrete floor from the intense radiation in the mixer-settlers below. All equipment that may require repair or replacement is located above the floor. The mixer-settler cells themselves were designed never to be entered.

ride were subsequently precipitated out, they would carry with them plutonium phosphate and plutonium fluoride in quantities of precipitate large enough to separate. By repeated dissolutions and precipitations, with intervening changes in oxidation state, plutonium was separated from uranium and fission products. Simple tanks were used for the dissolutions and precipitations; centrifuges were used for separating the precipitates.

The processes worked well and safely, without any significant damage to the health of workers or to the environment. Removal of the fission products was efficient, and more than 95 percent of the plutonium was recovered. Operating capacity so far exceeded expectations that of four chemical-separation buildings planned only three were built and only two were operated. Uranium was not recovered, and the volume of waste was large because of the bismuth phosphate and lanthanum fluoride that had been added. Considering how long it takes to design and construct nuclear power facilities today it seems almost unbelievable that barely two and a half years elapsed between the initial demonstration of the chain-reacting pile on December 2, 1942, and the explosion of the first plutonium bomb on July 16, 1945.

The important legacy of Hanford to the nuclear-fuel-reprocessing industry was the concept of remote operation and maintenance, together with the innovations of engineering design that were needed to implement it. The buildings were long, thick-walled concrete structures that enclosed the "canyons," or process spaces. The piping was embedded in the walls and ended in connectors precisely located at standard positions on the inside and near the top of the canyons. It was connected to the process equipment by accurately made jumpers that could be installed and removed by cranes that traveled the length of the canyons on rails. The crane operator, protected by heavy shielding and observing his tasks through a periscope, could remove and reinstall any of the equipment by using impact wrenches to manipulate the connectors at the ends of the jumpers. All liquids were transferred either by gravity or by steam-jet ejectors. Ingenious gang valves were developed to ensure that the steam lines were purged with air so that condensation could not suck radioactive solutions out of the shielded spaces.

After the war a major effort was



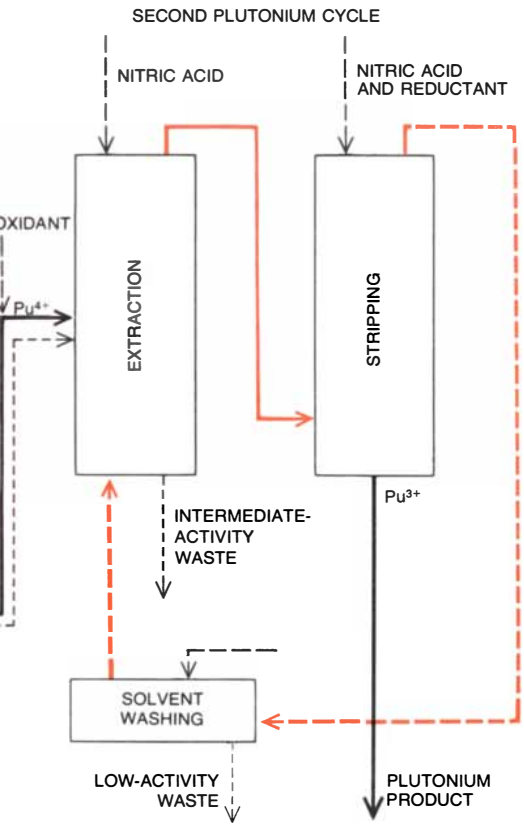
PUREX PROCESS for recovering uranium and plutonium from the spent fuel of power reactors employs TBP (tributyl phosphate) dissolved in a kerosenelike hydrocarbon as the separating agent. When uranium and plutonium ions are in a highly electron-deficient state, that is, are highly oxidized, they are more soluble in the TBP-hydrocarbon solution than they are in an aqueous solution. Under the same conditions the hundreds of radioactive by-products created when uranium-235 atoms fission in a reactor are more soluble in a strongly acid aqueous solution than in the organic one. This simplified diagram shows seven vertical columns in which organic and aqueous solutions are forced to travel countercurrently in intimate contact, so that substances more soluble in one solution than in the other can be efficiently separated. The feed mixture entering the first extraction column is the spent fuel in aqueous solution. In addition to the highly radioactive by-products it typically contains about 1 percent of unfissioned uranium 235, more than 90 percent of the nonfissionable isotope uranium 238 and between .5 and 1 percent of mixed plutonium isotopes, primarily plutonium 239 and plutonium 240, the first produced from uranium 238 by the capture of a neutron and the second from plutonium 239 by the capture of another neutron. The uranium ions are in a highly oxidized state, deficient in six electrons (U^{6+}); the plutonium ions are deficient in four electrons (Pu^{4+}). The aqueous feed enters the first extraction column near the middle; the TBP solvent enters at the bottom. The uranium and plutonium are extracted by the upflowing solvent; the fission products are "scrubbed" out of the solvent by the downflowing aqueous stream of nitric acid and leave from the bottom of the column. The uranium-plutonium mixture passes to the second, or partitioning, column, where the plutonium is "stripped" out of the solvent by countercurrent contact with nitric acid that contains a reductant that reduces the plutonium to

launched to develop technically superior processes that could operate continuously rather than in batches and that could recover both uranium and plutonium with high yields. Solvent extraction received the most attention because it had previously been successfully applied to the purification of uranium. In solvent extraction aqueous and organic solutions flow in opposite directions (countercurrently) through a column or some other kind of mixing chamber that disperses one of the solutions in small droplets through the other. In the solvents that were used hexavalent uranyl ions, $(UO_2)^{++}$, and plutonyl ions, $(PuO_2)^{++}$, together with tetravalent plutonium ions, Pu^{4+} (plutonium atoms from which four electrons have been removed), are soluble, whereas trivalent plutonium ions, Pu^{3+}, and fission-product ions are not. Thus the solvent can extract the uranium and plutonium (in its highly oxidized forms) from the aqueous feed solution, which retains most of the fission products. In separating the plutonium from the uranium the plutonium is reduced to the trivalent Pu^{3+}, making it insoluble in the solvent, which then contains all the uranium.

This play on oxidation states gave rise to the name Redox for the first solvent-extraction process to be applied on a large scale. The Redox process, with Hexone (methyl isobutyl ketone) as the organic solvent, was put into operation at Hanford in 1951. Later processes with other solvents exploited the same oxidation-reduction cycle. To force the highly oxidized ions of uranium and plutonium into the solvent high concentrations of nitrate ions are needed. In most chemical processing nitric acid is used to supply nitrate ions. Since the Redox solvent Hexone is decomposed by high concentrations of nitric acid, however, aluminum nitrate was used instead. This added greatly to the quantity of highly radioactive waste. Hexone also had the disadvantage of being highly volatile and flammable.

Shortly after the war the British built production reactors and a separation plant at Windscale in Cumbria. As an extraction solvent they chose Butex (β,β' dibutoxy diethyl ether). Butex is chemically stable in strong nitric acid, making it unnecessary to resort to aluminum nitrate. It is also denser and less volatile than Hexone, but it is more expensive. In the early 1950's, when the U.S. built a major new plant for producing plutonium and the hydrogen isotope tritium on the Savannah River near Aiken, S.C., tributyl phosphate (TBP) was selected for the solvent-extraction process. When TBP is dissolved in a kerosenelike solvent, it is chemically even stabler than Butex, is cheaper than Hexone and gives better separations than either. The TBP, or Purex, process is now used in all reprocessing plants.

The Purex process comprises three cycles of extraction with TBP. Extraction is preceded by a "head end" step in which the spent fuel is dissolved and the solution is clarified, a process that varies with the nature of the fuel and the cladding of the fuel rods. At the Savannah River Plant, where the reactors are fueled with natural uranium metal clad in aluminum, the cladding material is removed by dissolving it in an aqueous solution of sodium hydroxide and sodium nitrate. The uranium oxide elements that fuel all American power reactors are encased in long, slender tubes made either of stainless steel or of the zirconium alloy Zircaloy. Such rods are prepared for processing by chopping the tubes into short sections and dissolving out the oxide ("chop-leach"). (Chemical and electrochemical dissolution of the oxide fuel rods has been demonstrated, but it calls for process equipment made of alloys that are highly resistant to corrosion and adds to the volume of liquid wastes.) The solutions from the head-end dissolvers are usually centrifuged to remove finely divided solids that would interfere with the solvent extraction. A substance such as manganese dioxide is sometimes precipitated to help clarify the solution and carry down some of the fission products.



the 3+ state (Pu^{3+}), making it insoluble in the organic solvent. Simultaneously upflowing solvent scrubs the last traces of uranium from the aqueous solution of plutonium, which leaves from the bottom of the partitioning column. In the third, or stripping, column the uranium is removed from the organic solvent by dilute nitric acid. In the second uranium and plutonium cycles the extraction and stripping are repeated separately. In passing through the system, particularly in the first cycle, solvent is somewhat degraded by intense radiation and by chemical attack. Degradation products, along with traces of fission products, are removed from solvent with alkaline solutions.

When the separated uranium and plutonium streams emerge from the Purex process, they contain only about a millionth as much radioactivity due to fission products as the feed material did. At this low level of radioactivity the products in the two streams can be purified further and converted into the preferred final forms by fairly conventional chemical operations with relatively little radiation shielding. Evaporation, ion exchange, adsorption, precipitation and calcination have all been employed at one time or another. In the Government plants plutonium is reduced to the metallic form needed for weapons. If plutonium is ever used as fuel in nuclear power plants, plutonium oxide would be the preferred form, as is uranium oxide (U_3O_8). If the uranium is to be returned to the gaseous-diffusion plants for reenrichment, it is converted into uranium hexafluoride (UF_6), which is a gas at room temperature. Largely because of the differences between fuel forms two different practices have been adopted with regard to wastes. The wastes at Hanford and Savannah River are made strongly alkaline; this makes it possible to store them in tanks of carbon steel, which are placed in underground concrete vaults. Power-reactor wastes are concentrated in acid form and thus call for stainless-steel tanks.

The Purex process, with some modification, also lends itself to reprocessing the spent fuels from reactors using highly enriched uranium (such as the reactors of nuclear submarines) in which only traces of plutonium are formed. The chemical processing plant at the Idaho National Engineering Laboratory near Idaho Falls, Idaho, reprocesses the fuels from naval propulsion reactors and from research reactors of various kinds. The Idaho reprocessing plant differs markedly from the units at Hanford and Savannah River in being designed for direct (as opposed to remote) maintenance. The process equipment must be chemically decontaminated inside and out to allow men to enter the cells for repairs and replacements.

The efficiency of the Purex process depends heavily on the design of the solvent-extraction apparatus in which two immiscible liquids, one aqueous and one organic, are brought into intimate contact and then cleanly separated. This is done in an apparatus called a contactor. The simplest apparatus for countercurrent solvent extraction is the

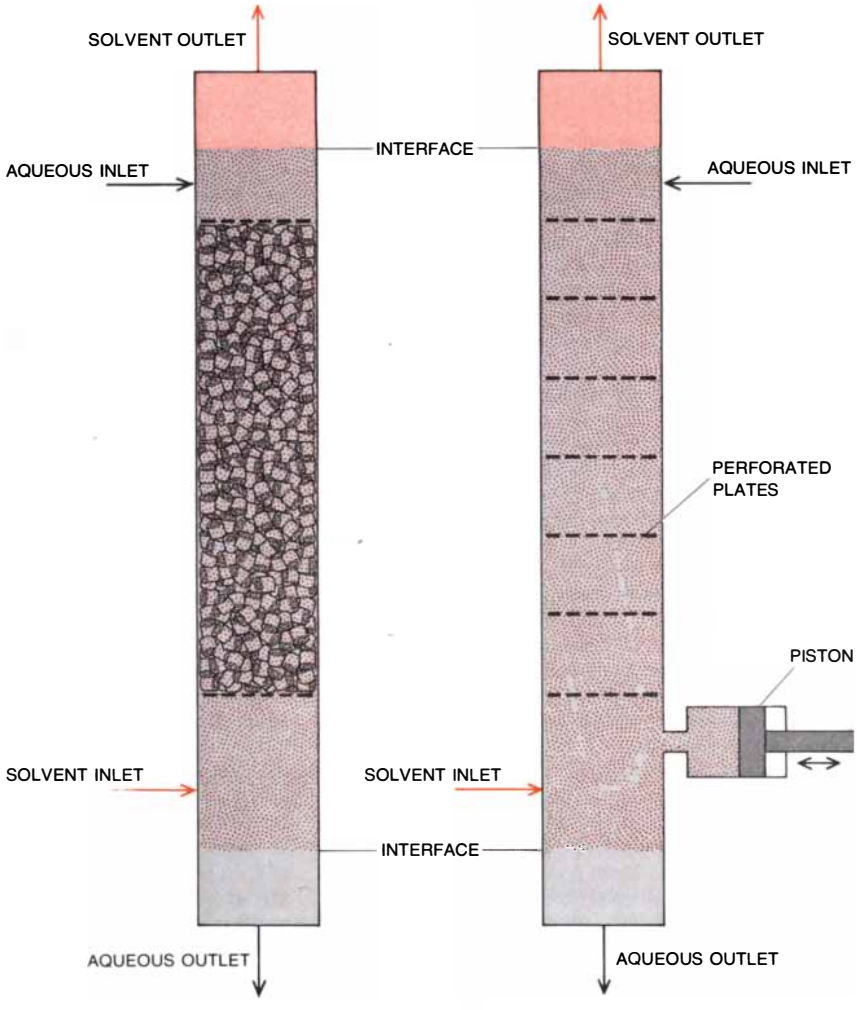
packed column, a vertical tube usually fitted with metal or ceramic rings that break up the liquid phases and direct them into tortuous paths through the column. The lighter organic solution flows up through the column as the heavier aqueous solution flows down. In such a column the mixing is not vigorous and the flow rates are low. As a result the column must be very tall to achieve a good separation, which complicates a plant that must be heavily shielded and must avoid the use of pumps. When packed columns were installed for the Butex process at Windscale, the result was a process building 20 stories high (with the fuel dissolver at the top) to allow the radioactive streams to flow downward by gravity.

The effectiveness of the extraction column can be greatly increased and its height can be reduced by "pulsing," so that the phases are drawn back and forth through perforated plates as they pass through the column. The pulsing can be done either by means of a piston or by applying air pressure to an external chamber. Pulsed columns were installed in the Purex plants at Hanford and at Idaho Falls.

One alternative to the extraction column is the "mixer-settler," in which the organic and the aqueous solutions are repeatedly mixed and separated in banks of from 12 to 24 horizontal stages, each consisting of a square mixing chamber at one end and a long settling chamber at the other. The mechanical agitator that mixes the solutions also propels the liquids from stage to stage. The chief drawback of mixer-settlers is the large volume of uranium and plutonium that is held up in liquid inventory. Because of the large holdup the solvent is subject to considerable damage from radiation and chemical activity. Among the advantages of the system are that the contactor can be readily adapted to remote maintenance, as it is at Savannah River, or be remote from the motors that drive the mixers, as it is at Windscale. Mixer-settlers are used in most of the European reprocessing plants.

An improvement on both the extraction column and the mixer-settler is a centrifugal contactor developed at Savannah River. The settling section that accounts for the large holdup of uranium and plutonium in the mixer-settler is replaced by a small centrifugal separator mounted on the same shaft as the mixing vanes. Typically arrayed in groups of six, the centrifugal units are more efficient than the mixer-settler, have only 2 percent of the volume, need only a small fraction of the time to come to a steady state of operation or to be flushed out and cause only about a fifth as much damage to the solvent. A few years ago an 18-stage centrifugal contactor replaced a 24-stage mixer-settler as the extraction contactor in the Savannah River Purex plant.

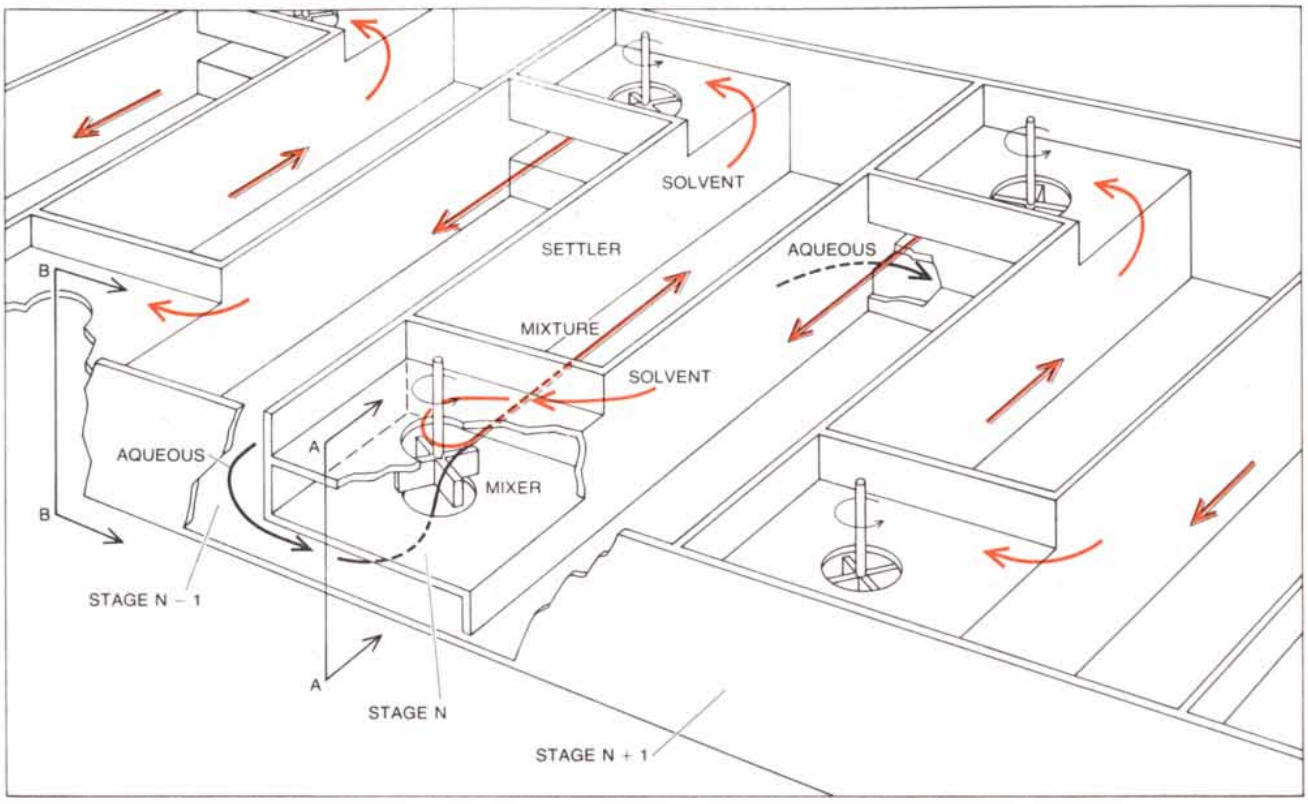
An axial-flow, multistage centrifugal contactor called the Robatel has recently been developed by a French company, Saint-Gobain Techniques Nouvelles. In this device eight stages are arrayed along the single vertical shaft of the centrifuge bowls. The apparatus has been selected as the extraction contactor for the first Purex cycle of the Barnwell plant of Allied-General Nuclear Services.

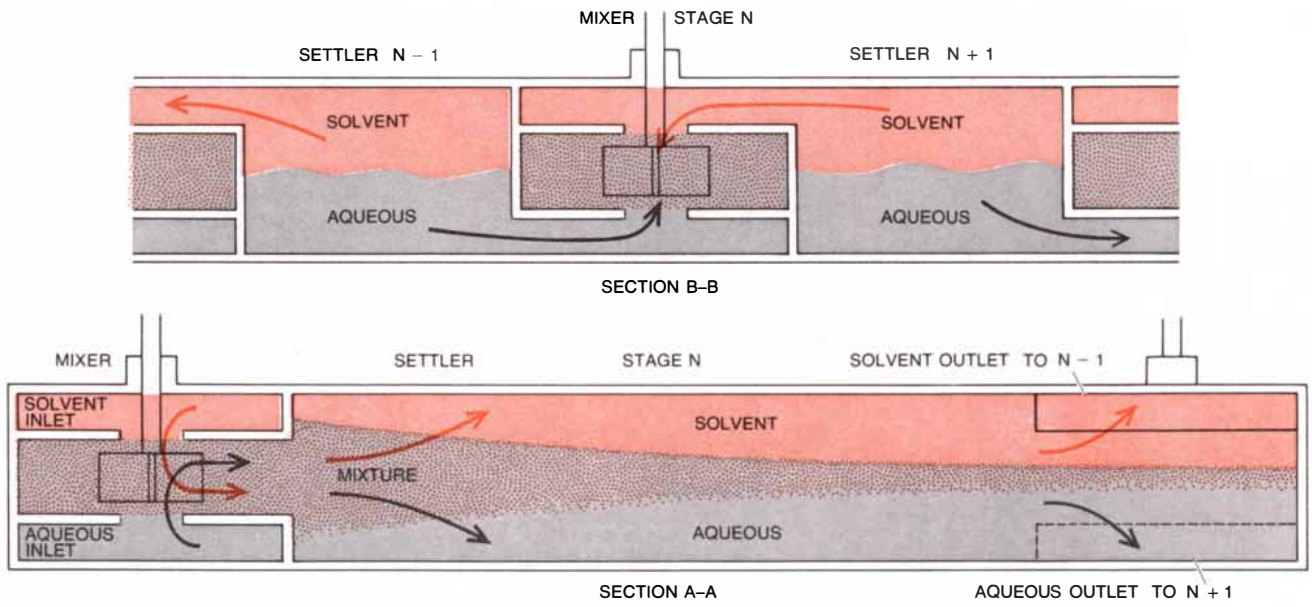


SIMPLE EXTRACTION COLUMNS were used to provide intimate contact between the solvent and aqueous solutions in the first spent-fuel-reprocessing plants. In the column at the left contact is provided by a packing of randomly oriented ceramic or metal objects, usually in the shape of rings or saddles. The aqueous solution in the column flows downward under the influence of gravity; the lighter-organic solution travels upward. A smaller, more efficient extractor (*right*) can be built if a piston or air pressure is employed to "pulse" the fluid in the column so that two solutions are repeatedly drawn back and forth through tiers of perforated plates.

The large-scale use of nuclear energy for the generation of electricity got under way in Britain before it did in the U.S. To reprocess the magnesium-alloy-clad uranium-metal fuel from their first power reactors the British chose to modify and expand the plant at Windscale, which had originally been built to separate weapons-grade plutonium. They designed the plant on the principle that the equipment inside the shielded cells where the most highly radioactive material was handled would never be repaired or modified. This no-maintenance principle called for materials and equipment of the highest quality. Reliability was ensured by building two complete primary separation plants, one to serve as a spare. In addition each plant had a complete spare dissolver and a spare first solvent-extraction contactor. The spare primary plant was never needed as such, and it was later modified and increased in capacity. In 1957 it began reprocessing power-reactor fuel. Decontamination and modification of the first plant were then found to be feasible, with the result that the modified original plant served the British nuclear power program until 1964.

In the early 1960's the British designed and built their second-generation reprocessing plant, this time based on



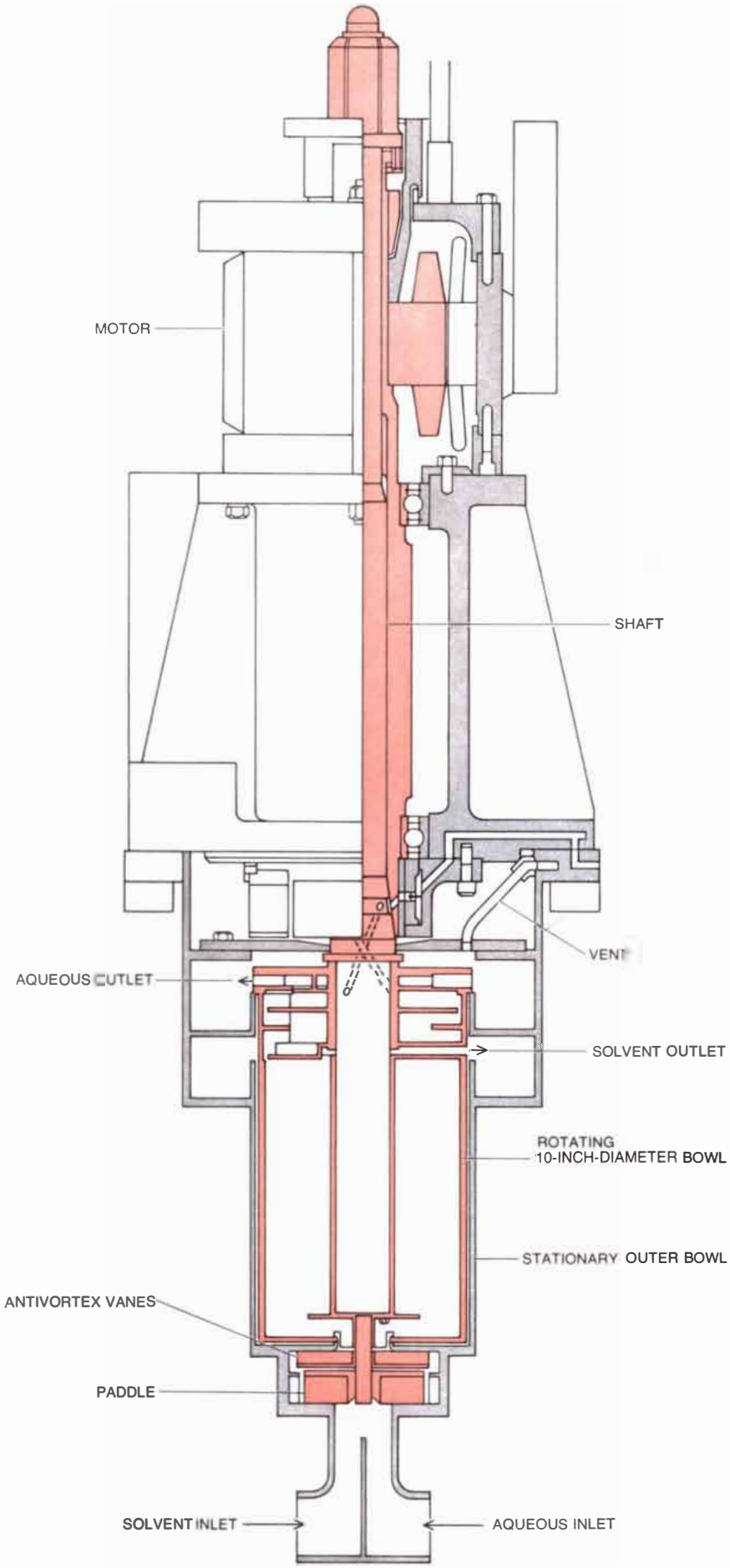


MIXER-SETTLERS, in which flow is maintained by paddles rather than by gravity, were first used at Savannah River Plant in the U.S. Aqueous and solvent solutions flow countercurrently through horizontal "stages." Each stage consists of mixing chamber and settling one.

Purex solvent instead of Butex. With a capacity to reprocess 2,000 to 2,500 metric tons of fuel per year, the new plant is the largest of its kind in the world. The no-maintenance principle was again followed. In 1969 a chop-leach dissolving facility was added as a head end to handle uranium oxide fuel (clad in either stainless steel or Zircaloy) that had been subjected to much longer "burnup" (exposure in the reactor) than earlier uranium-metal fuel rods and that as a result had a higher content of fission products. Chop-leach dissolving is followed by one cycle of Butex extraction to bring the fission-product content of the oxide fuel into line with that of the uranium-metal feed to the main plant.

There is also a small reprocessing plant in northern Scotland for the spent, highly enriched uranium fuel from the adjacent Dounreay reactor and from materials-testing reactors. At Dounreay the fuel cycle is completed under conditions that anticipate the more stringent requirements of later generations of commercial power reactors. Enriched-uranium fuel assemblies that have been irradiated to high burnup are reprocessed after short cooling times and are refabricated into new fuel elements.

The Windscale reprocessing plants (and the Dounreay operations as well) are now a part of British Nuclear Fuels Ltd., an independent (albeit government-owned) corporation that provides complete fuel-cycle services and has reprocessed spent nuclear fuels from other countries, including West Germany,



Italy, Japan, Spain and Sweden. It is a member of United Reprocessors GmbH, a joint Anglo-French-German company set up to coordinate requirements and operations in Europe.

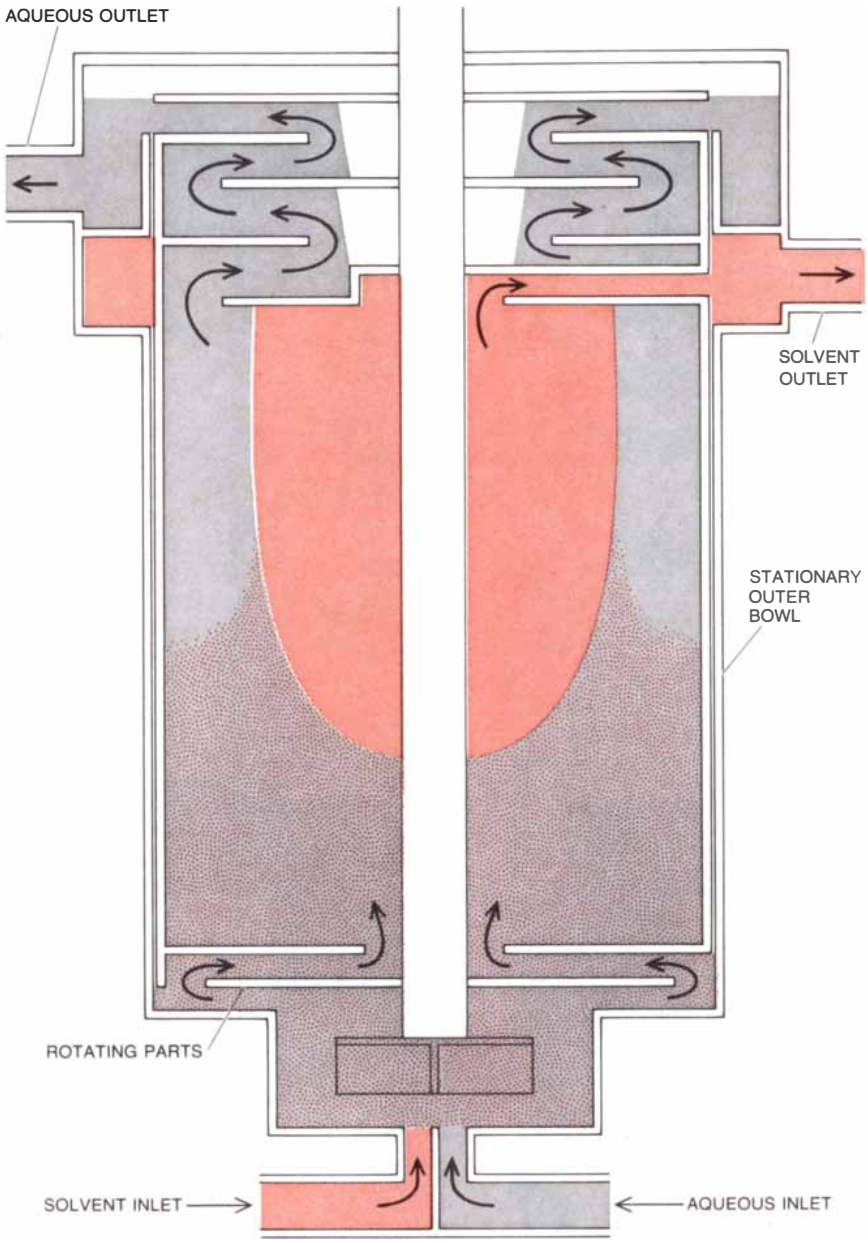
In the U.S. the Atomic Energy Commission, now merged into the Energy Research and Development Administration (ERDA), supported nuclear power by research and development in national laboratories, constructed demonstration reactors (such as the one at Shippingport, which was built in collaboration with public utilities) and stored (and in a few instances reprocessed) spent fuels from those reactors. The AEC did not, however, take the responsibility for either fuel fabrication or fuel reprocessing. The same policy continues under ERDA. Only the enrichment of uranium and the ultimate disposal of highly radioactive wastes are Government responsibilities.

Interest in the reprocessing of nuclear fuels developed among the suppliers of nuclear power equipment who felt the need to assure their customers of a closed fuel cycle, the chemical companies that had the necessary technological skill and background, and the oil companies that hoped to expand their operations into other energy sources. Several ventures into reprocessing emerged. The first, Nuclear Fuel Services (originally a subsidiary of W. R. Grace & Co. but now owned jointly by the Getty Oil Company and the Skelly Oil Company), designed and constructed a plant with a capacity of 300 tons of spent fuel per year on a site owned by the state of New York in West Valley, N.Y. After six years of operation the plant was shut down in 1972 for a planned expansion to 750 tons per year, for the correction of some deficiencies in the process, for the improvement of environmental-protection features and for the installation of waste facilities needed to meet new regulatory requirements. The plant used the Purex process in pulsed columns. Fuel was prepared for processing by chop-leach. The chop-leach equipment could be maintained or replaced remotely; the Purex-process cells were maintained directly. At last reports, however, the estimated cost of the modifications had risen from $15 million to $600 million, and Nuclear Fuel Services had withdrawn its application to the Nuclear Regulatory Commission for permission to reopen the plant.

CENTRIFUGAL CONTACTOR for mixing and separating solvent and aqueous phases was developed at the Savannah River laboratory of the Energy Research and Development Administration. Role of settling chamber in mixer-settler is taken over by a bowl on same shaft as mixing paddle. Drive motor, with its frame and bearings, is remotely replaceable.

The General Electric Company had meanwhile become convinced that relatively small reprocessing plants might be built to serve a group of power reactors within a short shipping radius. General Electric designed and built such a plant, the Midwest Fuel Recovery Plant at Morris, Ill., near the Dresden nuclear power station of the Commonwealth Edison Company. With a capacity of 300 tons per year, the Morris plant embodied major departures from the typical Purex-TBP process, with the aim of minimizing the contribution of reprocessing costs to the cost of nuclear power. The General Electric Aquafluor process involved TBP solvent extraction for the separation of uranium and plutonium from most of the fission products, ion exchange for separating uranium and plutonium from each other, and fluidized beds for the calcination of uranyl nitrate to the oxide (UO_3) and for the conversion of the oxide to the hexafluoride (UF_6).

Instead of the usual second solvent-extraction cycle for the uranium, General Electric incorporated a separation step that exploited differences in volatility for separating the fluorides of the fission products from the UF_6. This step reduced costs and eliminated some liquid waste, but it entailed the remote handling of radioactive powders. In the course of testing the plant equipment with nonradioactive feeds it was concluded that the problems of handling fine radioactive solids were far greater than had been anticipated and would preclude successful operation of the plant. It now seems that the plant cannot be modified economically to avoid such difficulties and meet the current requirements of the Nuclear Regulatory Commission.

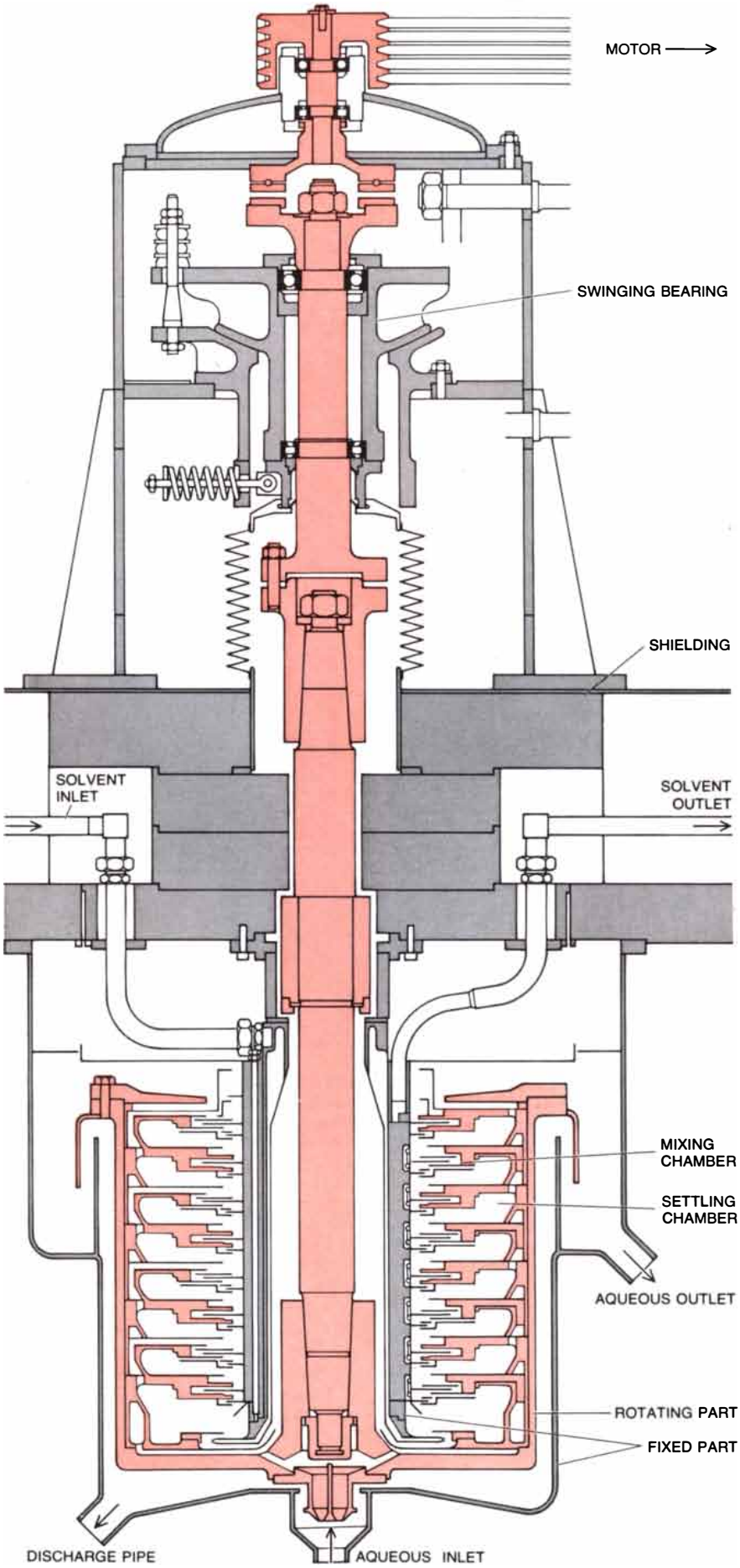


FLOW PATH IN A CENTRIFUGAL CONTACTOR is depicted schematically. After thorough mixing the organic and aqueous solutions travel upward into a rotating bowl where they are separated centrifugally. Heavier aqueous solution is thrown to outside of bowl; lighter organic solution is driven inward. Baffles at top of bowl direct two solutions to separate ports.

In 1968 the Allied Chemical Corporation announced plans to build a 1,500-ton-per-year fuel-reprocessing plant on land in the Barnwell County industrial park, adjacent to (originally part of) the site of the Government's Savannah River Plant. Allied Chemical was joined by the General Atomic Company, jointly owned by the Gulf Oil Corporation and the Royal Dutch/Shell Group of Companies, as co-owner of Allied-General Nuclear Services, the operator of the Barnwell facility. Apart from its proximity, the Barnwell plant is independent of the Savannah River Plant. Construction at Barnwell was begun in 1971, and the originally planned facilities are now complete. They provide for receiving and storing fuel, chop-leach dissolving, Purex separations, storage of high-activity wastes and plutonium nitrate product, and the conversion of uranyl nitrate product into uranium hexafluoride.

Design and construction at Barnwell of "tail end" facilities for the solidification of the waste for shipment to a Federal repository and for the conversion of plutonium nitrate to solid plutonium oxide await decisions by the Nuclear Regulatory Commission and ERDA on the specifications and destinations of those materials. So far Allied-General Nuclear Services has invested some $250 million in the Barnwell plant (more than three times the original expectation); the waste and plutonium facilities are expected to cost another $250 million. Half a billion dollars may seem like a large investment for a single reprocessing plant, but in the overall economics of nuclear power the outlay represents less than 1.5 percent of the value of the 50 to 60 nuclear power reactors whose spent fuel the Barnwell plant can reprocess.

In the Allied-General Nuclear Services separations facility the spent fuel will be chopped into short lengths by a shearing device that was conceived by its engineers and designed and built by Saint-Gobain Techniques Nouvelles. The uranium oxide pellets will be dissolved continuously from the cladding hulls in a series of vessels where fresh acid leaches the last traces of fuel from a batch of hulls. Solid particles are removed from the solution by centrifugation. There are two innovations in the Purex system: the first extraction contactor is the Saint-Gobain centrifugal



unit I described above, and the separation of plutonium is achieved by reducing the plutonium electrolytically in an "electropulse" column, a development of the Allied-General Nuclear Services technical staff. The other contactors are also pulsed columns. Equipment that is subject to mechanical or electrical failure or to unusually corrosive conditions can be replaced remotely; the rest of the equipment is designed for direct maintenance.

Exxon Nuclear is a supplier of uranium and of reactor fuel assemblies and is actively interested in the rest of the fuel cycle, including enrichment and reprocessing. Earlier this year Exxon announced plans to build a 1,500-ton-per-year reprocessing plant on land that is now part of the ERDA site at Oak Ridge, Tenn. The company is awaiting a construction permit from the Nuclear Regulatory Commission. Although other companies have from time to time expressed interest in fuel reprocessing, no other commitments have been made.

One industry executive has summed up the current situation by saying: "At this moment the nuclear-fuel cycle does not exist." In the U.S., at least, this is true; even the design and construction of modified and new facilities are at a standstill pending the resolution of environmental and regulatory impasses.

Hearings on the recycling of plutonium as an oxide mixed with uranium are just getting under way, and waste handling is in limbo until the final disposal site and specifications are decided. Even receipt and storage of spent fuel at Barnwell awaits license hearings that are only now about to begin. The separations facility is ready and could be operated, with interim storage of waste and plutonium in solutions, but this too awaits completion of environmental and safety appraisals and subsequent license hearings. There is doubt about whether the plant will be cleared for start-up before the end of the decade.

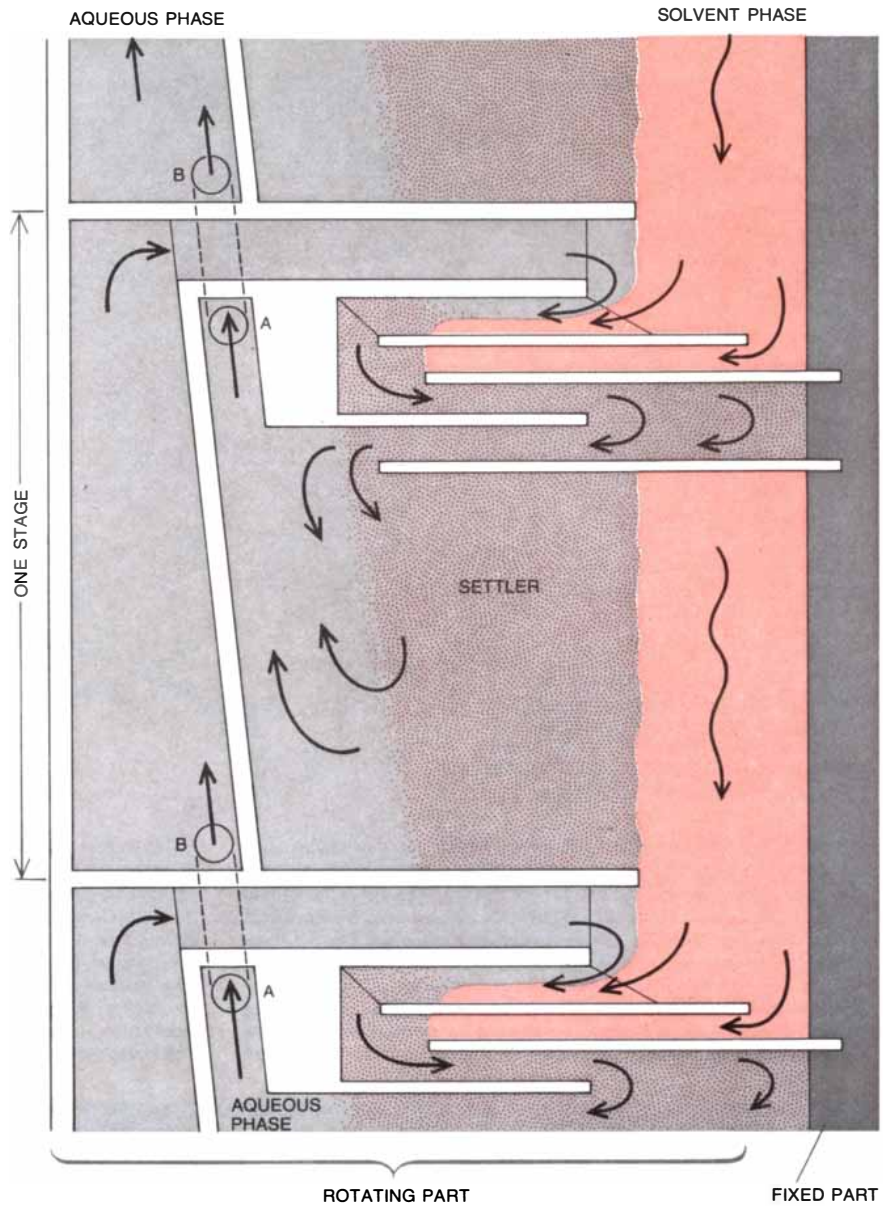
The situation abroad is strikingly different. Both the British and the French have relied on military production facilities to process spent uranium from the first or second generation of power reactors, which used metallic fuel rather than oxide. The construction of additional facilities to reprocess uranium oxide fuel from the newer light-water (as opposed to gas-cooled) reactors has fallen behind schedule, but not seriously. The Windscale head-end facility for oxide fuel operated from 1970 to 1973,

MULTISTAGE CONTACTOR called the Robatel has been developed by the French firm Saint-Gobain Techniques Nouvelles. The rotating bowl of this centrifugal machine has a diameter of 80 centimeters, which is about three times diameter of the bowl in the Savannah River unit. The path through one stage of Robatel is shown on opposite page.

when it was shut down after a small release of radioactivity that led to a comprehensive review of the processing of highly irradiated oxide fuels. The British have now decided not to modify or rebuild the head-end facility and are planning to put up two more oxide-reprocessing plants with a capacity of 1,500 metric tons per year each, to be completed during the 1980's.

The original French reprocessing plant at Marcoule, with a capacity of processing 1,000 tons of uranium metal per year, has been running since 1958. A second plant of the same capacity went into operation at La Hague in 1967. A head-end facility able to handle about 800 tons of oxide fuel per year was recently added to the La Hague plant. The French are now proposing to build two more complete oxide-processing facilities at La Hague, each with a capacity of 800 tons per year, the first to be ready by 1984 and the second by 1986.

In West Germany a group of four chemical and nuclear engineering companies, which has been operating a small demonstration reprocessing plant, is now selecting a site for a plant with a 1,500-ton-per-year capacity that is expected to be operating by the late 1980's. The overall scheduling of European reprocessing facilities has been guided since 1971 by United Reprocessors, a consortium of British, French and West German enterprises. Its goal is to provide an integrated reprocessing capacity of about 20,000 tons per year by the early 1980's. There are small demonstration plants in Japan and India. Brazil and Pakistan have recently negotiated respectively with West Germany and France for the purchase of full-scale plants. Japan has also announced plans to build a large plant.

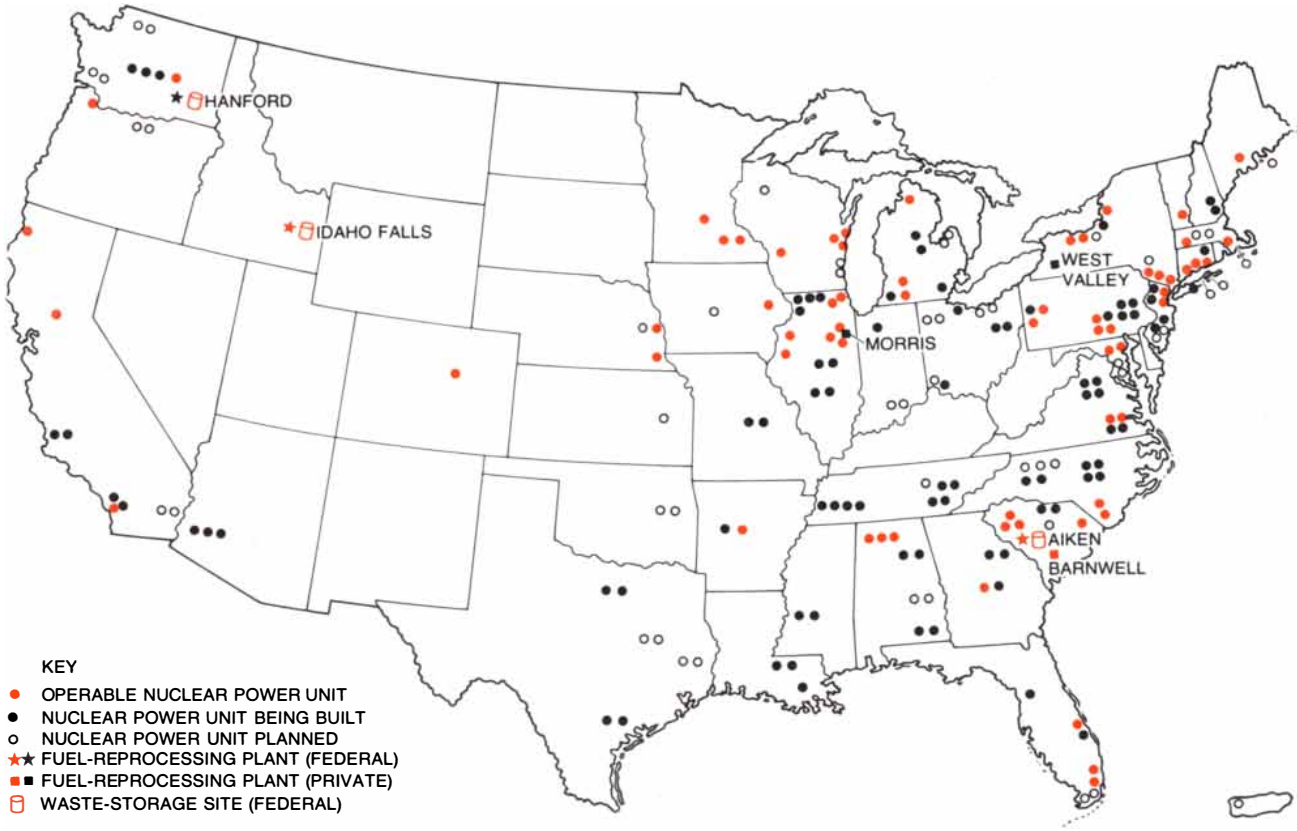


FLOW SCHEME IN THE ROBATEL provides for eight stages of mixing and settling arranged one above the other. The schematic diagram shows the flow through a single stage. Briefly, the organic solution, traveling downward on the inside of the rotating bowl, is repeatedly mixed with the aqueous solution, which is conducted upward through a series of ports and baffles. Flow of organic solution is readily followed from diagram. At each stage aqueous solution leaves settler through ports labeled *A* and reappears in stage above through ports labeled *B*.

How can the U.S. nuclear power industry continue to operate without the reprocessing of its spent fuels? For the present there is enough uranium-enrichment capacity to allow once-through operation of existing nuclear power reactors, partly because the expansion of nuclear power facilities has been greatly retarded as a result of the economic slump, high construction costs and licensing delays. The volume of spent nuclear fuel accumulated per year is still manageable; in 1977 about 1,100 tons will be discharged, and its storage for long periods is simple and safe. The high-integrity, corrosion-resistant cladding is more than adequate to contain the fuel in the high-purity water of the storage basins. The capacity of the storage basins is being taxed, however, and modifications are being made to increase the size of some of them. The storage basin at Morris is in service, and the one at Barnwell has been completed.

Once-through operation of nuclear power reactors and the increasing investment in spent-fuel inventory add substantially to the cost of electric power from the nuclear plants, perhaps as much as 20 percent. These costs must ultimately be covered by the consumer. Even more important, the spent fuel constitutes a high-grade energy resource that must ultimately be "mined." The fuel cycle needs to be closed so that the technologies for reactor-fuel fabrication and for reprocessing can remain in step with reactor technology and meet their mutual requirements. It is particularly desirable that the commercial reprocessors have experienced staffs and demonstrated processes before they are called on to take up the more demanding task of reprocessing plutonium fuels from breeder reactors and other advanced systems with high burnup rates and perhaps shorter cooling periods.

The U.S. has now had more than three decades of highly successful experience in reprocessing reactor fuels to extract hundreds of tons of plutonium, with no proof that these activities have done any significant harm to man or his environment. In spite of this experience critics of nuclear power point to such hazards as possible leaks from existing liquid-storage tanks containing highly radioactive wastes, the long life of highly radioactive wastes under any storage procedure and the harm that could be done by the routine discharge of effluents with



SIXTY-TWO FISSION POWER REACTORS are now licensed to operate in the U.S. at 44 sites. Another 72 reactors are under construction and 61 more are in the planning stage. The operating plants have a total capacity of 44,650 megawatts, which represents just over 8 percent of the total U.S. electric-generating capacity. The 72 reactors under construction will add another 75,500 megawatts of capacity. Only one privately owned spent-fuel-reprocessing plant is substantially finished and awaiting a license to operate: the $500-million plant of Allied-General Nuclear Services in Barnwell, S.C. Two other reprocessing plants (*black squares*) have been constructed, one by the General Electric Company at Morris, Ill., the other by Nuclear Fuel Services, Inc., at West Valley, N.Y., but their owners have no present plans to put them into operation. The Federal Government has three major fuel-reprocessing facilities: one at Hanford, Wash. (now shut down), one on the Savannah River near Aiken, S.C., and one at Idaho Falls, Idaho. At these three sites the U.S. has also stored some 75 million gallons of radioactive wastes, the residues from more than 30 years of processing spent fuels, chiefly for extraction of plutonium. Fuel from power reactors is stored in pools adjacent to power plants and at reprocessing plants, including those at Morris and West Valley.

CHEMICAL REPROCESSING "CANYON," 800 feet long, at the Government's Savannah River Plant is one of two parallel remote-maintenance facilities. All piping and equipment can be removed and replaced by an operator riding in a heavily shielded crane that travels length of canyon on rails visible on facing walls. Pipe sections are balanced so that they hang level when they are lifted by crane. Connectors are operated by wrenches manipulated from crane. Reactors at plant were designed primarily to produce plutonium and tritium.

very low levels of radioactivity, by accidents in the reprocessing plants and by the theft of plutonium by terrorists. It is not possible in this article to answer all the questions that have been raised. Some of the known facts can nonetheless be discussed.

The principal fission products in aged high-radioactivity wastes are cesium 137 and strontium 90. Such wastes also contain traces of plutonium and uranium. Cesium 137 and strontium 90 have half-lives of about 30 years, so that several centuries of storage are needed for them to decay to negligible levels. (Twenty half-lives, or a factor of a million, are enough to leave most waste solutions innocuous.) The half-life of plutonium, however, is 24,000 years, but since it is a valuable product its loss in waste is kept as low as is practical. Typical wastes contain less than .1 percent of plutonium. At present all high-radioactivity waste is in solutions, sludges and masses of inorganic salts in underground tanks; none has been committed to ultimate disposal. The tanks are monitored, and the wastes can be (and have been) transferred to new tanks as the need arises.

There have been leaks in some of the older tanks at Hanford and Savannah River, but as could have been predicted from the characteristics of the wastes and the soils, the movement of the wastes away from the points of leakage has been slight. Strontium and plutonium are highly insoluble under the chemical conditions prevailing in the tanks, and cesium is strongly adsorbed by clay minerals in the soil. As successive groups of tanks have been built, standards of construction have been raised and the integrity of storage has been enhanced.

The alkaline Hanford and Savannah River wastes contain large concentrations of aluminum, iron and sodium salts, so that their volume is substantial (roughly 75 million gallons at present). On the other hand, only about 250 liters (65 gallons) of concentrated, acid, high-radioactivity waste remains from the reprocessing of a ton of power-reactor fuel. This amount can be reduced by demonstrated processes to as little as 75 liters of vitreous solid. The present policy of the Government is that the wastes shall be converted into solids by the reprocessors within 10 years of their production and that they shall then be delivered to Government sites for long-term storage.

The form of the wastes and the place for their ultimate disposal are technical problems that now require decisions and development rather than research. The places will almost certainly be geological formations; natural salt beds and other crystalline or sedimentary bedrock formations show promise. Salt deposits, and geological disposal in general, received a severe setback in public acceptance, however, when an abandoned salt mine in Kansas that had served for disposal tests was designated as the first site for actual demonstration disposals. It developed that this old mine was not well enough isolated from active salt workings nearby, and the project was abandoned.

Airborne and aqueous effluents from reprocessing plants normally carry the fission products krypton 85 and tritium, along with certain radioactive secondary by-products such as carbon 14, out into the environment. Although in total curies of radiation emitted the quantities of these substances are large, their radioactive, physical, chemical and biological characteristics are such that the radiation dose to man is a very small fraction of the dose he inescapably receives from the natural radioactivity in the environment. Some groups object to these routine releases on the grounds that any increase in the total dose of radiation, no matter how small, is harmful. This is the "linear hypothesis," based on the linear extrapolation of effects that can be observed at high doses to effects that cannot be observed at low doses.

Natural radioactivity exposes every person on the earth to an average annual dose of radiation amounting to about 100 millirems. In some populated areas the natural dose is several times higher. (For the purposes of comparison the official limit on the amount of radiation to which an individual worker in a nuclear plant may be exposed in the course of a year is five rems, or 50 times higher.) The amount of radiation added by nuclear operations is only a few millirems in the worst locations near the nuclear-plant fence. These small increases can be reduced, but only at great cost and in some cases with the substitution of other hazards. (An example is the storage of large quantities of krypton-85 gas under high pressure.)

Two general principles stated by the Committee on the Biological Effects of Ionizing Radiations of the National Academy of Sciences are pertinent. The first is: "No exposure to ionizing radiation should be permitted without the expectation of a commensurate benefit." The second is: "The public must be protected from radiation, but not to the extent that the degree of protection provided results in the substitution of a worse hazard for the radiation avoided. Additionally there should not be attempted the reduction of small risks even further at the cost of large sums of money that, spent otherwise, would clearly produce greater benefit."

Fears of accidents in the reprocessing plants have little foundation. The careful control required to maintain the efficiency of the process minimizes the probability of an accident. Moreover, the heavy shielding and sealed enclosures needed for routine protection from radiation confine an accidental release of radioactivity to a small area. The possibility that a critical mass of a fissionable isotope might accumulate is an understandable concern over an industry that grew out of the atomic bomb. The first effect of an accidental accumulation of a critical mass, however, is the almost instantaneous dispersal of the material, which immediately halts the chain reaction. The maximum energy release is small (equivalent to the combustion of between half a liter and five liters of gasoline), so that there is little damage to facilities and little dispersal of radioactivity. The burst of radiation, however, is serious, and a nearby worker could receive a grave dose. In the 30 years that the Government facilities have been operated there have been 12 accumulations of critical mass, five of them in chemical processing plants or laboratories. There was one fatality, which equaled the number from drowning and from shooting during the same period in those facilities. Chemical explosions and fires have had much more serious consequences in nuclear plants, but these too have had no significant offsite effects.

To many the greatest potential for disaster seems to be the possibility of terrorists' obtaining plutonium and making a bomb. The obstacles in the way of such a feat are great. Even a moderately effective bomb is a considerable technological achievement, and it is more difficult to make a bomb from power-reactor plutonium than from plutonium produced specifically for weapons. It is not generally appreciated that during the long exposure of fuel in a power reactor there is an accumulation of plutonium isotopes other than plutonium 239, particularly plutonium 240, which make it very much more difficult to assemble a supercritical mass of plutonium without an inefficient premature explosion. Weapons-grade plutonium is made with much shorter exposure in the reactor. Moreover, the radiation emitted by plutonium is easy to detect with sensitive instruments. (Such instruments can detect .25 gram in a volume of radioactive waste materials measuring several cubic feet.)

Diluting the plutonium oxide with uranium oxide before it is shipped from the reprocessing plant or "denaturing" it with a more radioactive material are possible deterrents to the hijacking of shipments. Such stratagems seem trivial, however, when one considers that there are tens of thousands of plutonium-containing weapons dispersed around the world and still more in weapons-fabrication plants. Perhaps our best hope is that someday plutonium will be more valuable for power-reactor fuel than for weapons, and that the nations will then beat their bombs into fuel rods.

Negative Aftereffects in Visual Perception

You will see one if you stare at a waterfall for a short time and then look away; the surrounding scene will seem to move slowly upward. The study of such illusions yields information on perceptual systems

by Olga Eizner Favreau and Michael C. Corballis

It is a common experience to look at a bright light and to find that a dark image of the object remains in the visual field for some time afterward. The phenomenon is called a negative afterimage (negative because the object was bright and the image is dark). A similar phenomenon can be experienced by staring for several minutes at something that is moving in a uniform direction, as a waterfall does, and then turning the gaze away; the surrounding scene will appear to drift slowly in the opposite direction. This is a negative aftereffect. Afterimages and aftereffects are illusions, reminding one that the senses are sometimes imperfect mediators between the external world and one's perception of it. The study of such illusions is valuable in psychology for the clues they provide to how the sense organs and the nervous system function in processing information.

Afterimages and aftereffects are encountered in a variety of forms. For example, afterimages of colored objects appear in colors that are complementary to the colors of the objects. If you stare at a patch of green for a minute or so and then look at a blank field, you can expect to see a reddish patch of the same shape [*see illustration on opposite page*].

In addition to motion aftereffects of the kind evoked by watching a waterfall one can experience figural aftereffects. For example, if you look at a line that is tilted about 15 degrees from the vertical, a line that is actually vertical may appear to be tilted in the opposite direction [*see bottom illustration on page 47*]. A related aftereffect can be observed if you look at a curved line for a time; a straight line then seems to curve the other way.

Aftereffects are by no means limited to vision. If someone is blindfolded and then runs a finger back and forth along a curved rod, a straight rod will seem to be curved the other way. Similarly, as has been demonstrated by Stuart M. Anstis of York University, if one listens repeatedly to a tone that increases in intensity, a tone of constant intensity is likely to sound as though it is decreasing in intensity. Here we shall focus on visual aftereffects, since they have been the most intensively examined.

A number of investigators in the 19th century thought motion aftereffects might be related to movements of the eyes. Exposure to a moving pattern induces the eyes to follow the motion of the pattern. If the eyes tend to persist in the same pattern of scanning when the movement is no longer there, a stationary pattern might then seem to move in the opposite direction.

In 1850, however, this hypothesis was discredited by the Belgian physicist Joseph Plateau on the basis of work with rotating spirals. Such a spiral appears either to expand or to contract, depending on the direction of rotation. Plateau found that if one watches an expanding spiral for a few minutes, a stationary spiral then seems to contract; conversely, a contracting spiral induces an aftereffect of expansion. The spiral aftereffect cannot be explained simply in terms of eye movements, because both expansion and contraction consist of movement in all directions at once.

Another explanation for aftereffects is the concept of normalization proposed by J. J. Gibson of Cornell University. He argued that a prolonged exposure to a stimulus that deviates in some way from an established norm might serve to redefine the norm. For example, an exposure to a line that is tilted slightly from the vertical might induce the observer to recalibrate his conception of the vertical toward the line. A truly vertical line would then be seen as being tilted in the other direction. This hypothesis may be partly correct, but it cannot easily account for aftereffects that arise when no obvious norm is involved. As Donald E. Mitchell and Darwin W. Muir of Dalhousie University have shown, the tilt aftereffect induced with a stimulus of oblique lines is similar in both magnitude and direction to the aftereffects induced with vertical and horizontal lines.

In recent years attempts to understand visual aftereffects have drawn increasingly on concepts derived from the growing body of knowledge of the neurophysiology of the visual system. Although most of this work is based on recordings made with microelectrodes from individual neurons, or nerve cells, in the visual system of such animals as cats and monkeys, a number of psychologists have been quick to extrapolate the findings to human vision. The exchange has also gone the other way: concepts derived from work on aftereffects in human beings preceded fundamental discoveries in the neurophysiology of vision in other primates. We hope to convey something of the flavor of this exchange between disciplines.

Light reaching the eye is focused by the lens to form a two-dimensional image on the retina. Light-sensitive receptors there convert the image into a spatial pattern of neural impulses. The impulses are transmitted from the receptors to a layer of neurons called bipolar cells and then to another layer called retinal ganglion cells. Fibers from the retinal ganglion cells make up the optic nerve, which carries the neural information from the retina to the brain.

Negative and complementary afterimages probably depend largely on the properties of cells in the retina. It is easy to demonstrate that an afterimage moves about as one moves one's eyes and that its location is perfectly correlated with the position of the eyes; it is as though the afterimage were painted on the retina. In contrast, objects actually

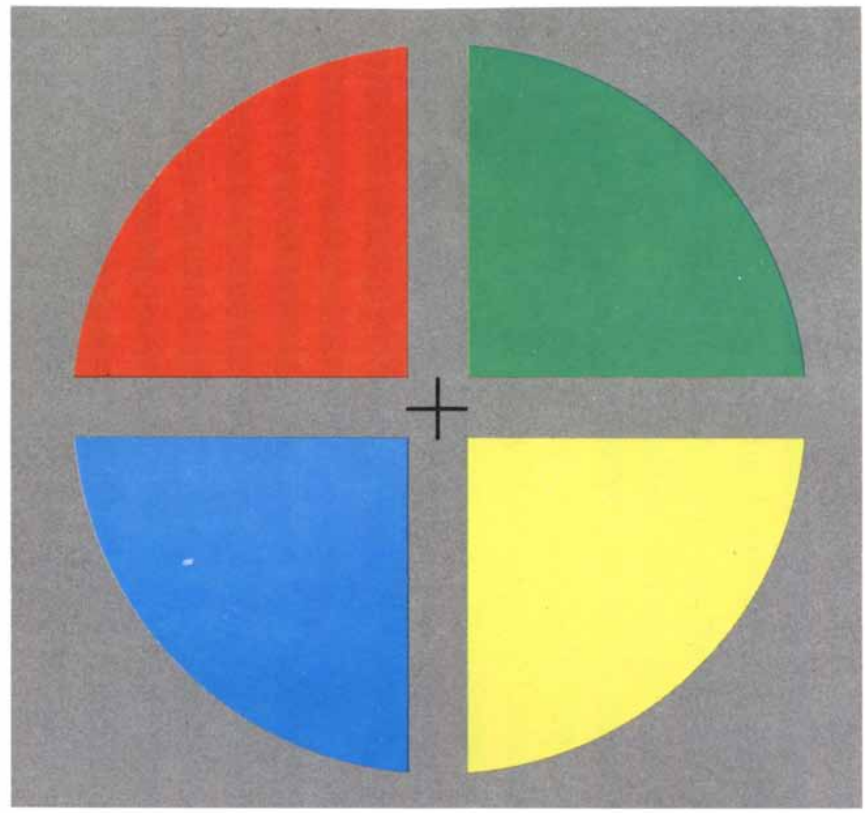
present in the visual field appear to remain fixed if one moves one's eyes. These observations hold only for normal, voluntary eye movements. The situation is reversed if one moves an eye passively, as by pressing at the corner of the eye with a finger; then objects in the real world appear to move but an afterimage remains motionless. Both kinds of observation show that afterimages are formed at a level of processing preceding the one where the perceived location of objects in space is "corrected" for voluntary eye movements.

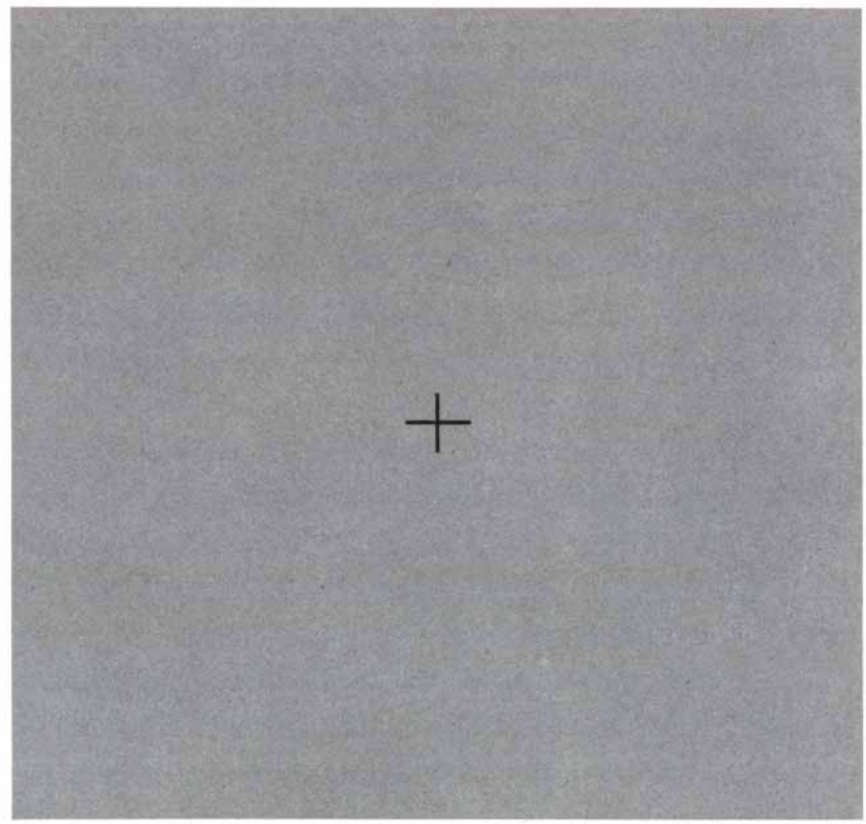
It is also easy to show that afterimages do not transfer from one eye to the other. The reader can verify this finding by looking at the illustration at the right for about 40 seconds with a hand over one eye. The afterimage will then be visible against a plain surface only to the exposed eye.

One can explain these phenomena by supposing cells in the retina, including the receptors, become temporarily fatigued or adapted after a long stimulation. According to this reasoning, if one looks at, say, a white patch, cells responsive to white light become less responsive, leaving an impression of a dark patch if the gaze is shifted to a uniform field. Complementary afterimages (red following green, for example) can be explained in a similar way.

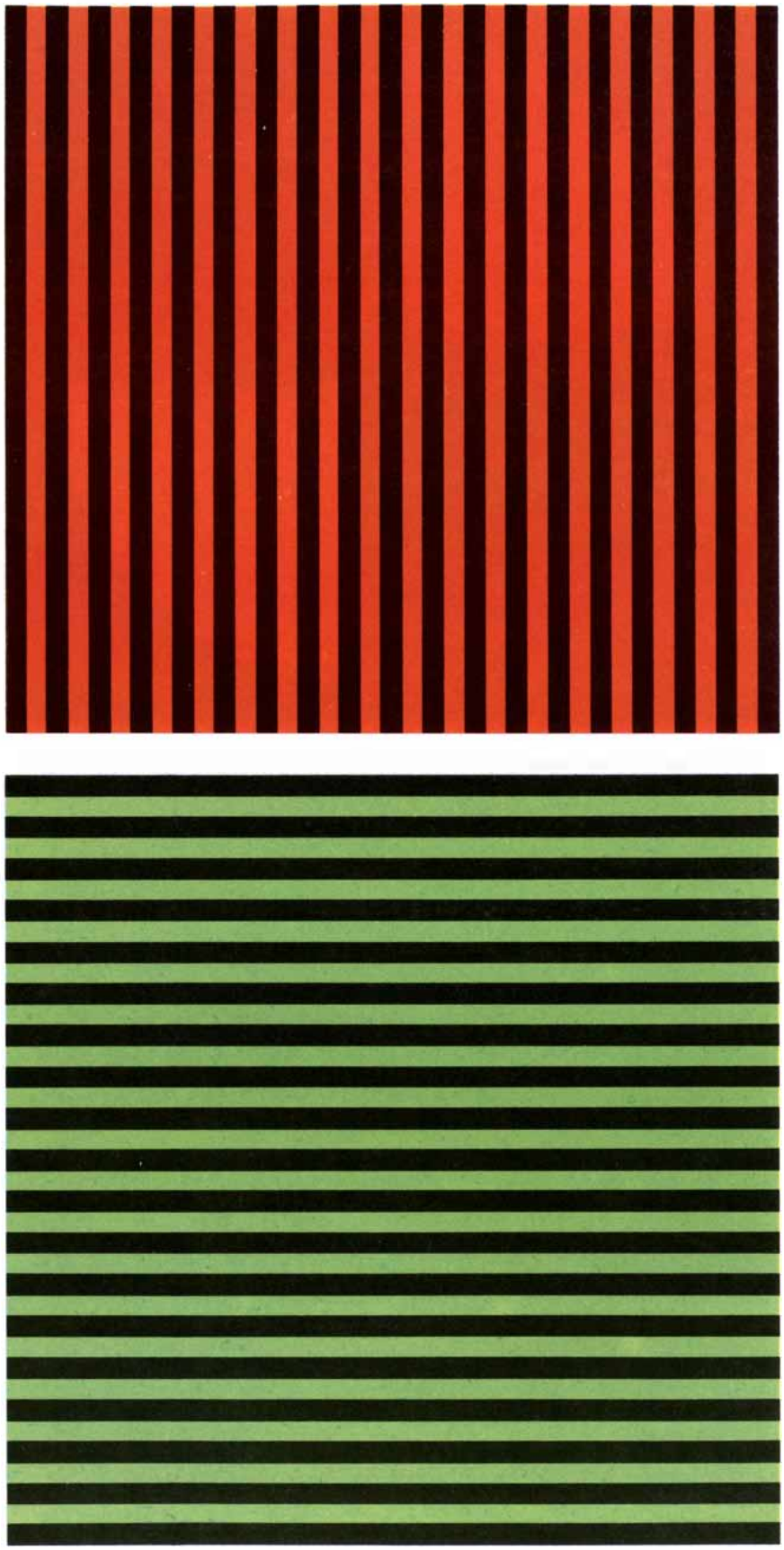
Neurons beyond the receptors may also contribute to afterimages. They include the bipolar and ganglion cells in the retina and possibly cells in the lateral geniculate nucleus, a relay station in the brain that receives its input directly from the retinal ganglion cells. Among the retinal ganglion cells and the lateral geniculate cells are cells that typically exhibit what is termed "opponent process" organization, meaning that a cell increases its normal rate of firing in response to one color but decreases it in response to the complementary color. Opponent-process cells might contribute to afterimages in two ways. Suppose one views a uniform green field for a period of time. The cells that fire at an increased rate for green (they are called green-on, red-off cells) may become fatigued, so that if one subsequently views a uniform white field, the reduced firing of these cells is interpreted as redness. Conversely, red-on, green-off cells would be depressed while one was looking at a green field and might subsequently "rebound" to enhance the impression of redness.

Whereas afterimages depend on the fatigue of cells in the early stages of visual processing, figural and motion aftereffects appear to depend on properties of neurons at a higher level, perhaps in the visual cortex. The study of such aftereffects was greatly stimulated by the pioneering discoveries of David H.





NEGATIVE AFTERIMAGE is the simplest kind of negative aftereffect. Here the afterimage will appear in the color that is complementary to the color you look at. If you fix your gaze on the cross at the center of the colors for about a minute and then look at the gray field at the bottom of the page, you should see patches that are in the complementary colors of the original: the green, yellow, blue and red will be replaced respectively by red, blue, yellow and green.



CONTINGENT AFTEREFFECT is demonstrated by these two grids and the pattern in the illustration on the opposite page. Look alternately at one grid and then the other for about 10 seconds each for 10 minutes. Then look at the pattern on the opposite page. Its horizontal lines should appear reddish and its vertical lines greenish. If the page is turned 90 degrees, the color relations reverse. The phenomenon is termed an orientation-contingent color aftereffect.

Hubel and Torsten N. Wiesel of the Harvard Medical School on the properties of neurons in the visual cortex of the cat brain [see "The Visual Cortex of the Brain," by David H. Hubel; SCIENTIFIC AMERICAN, November, 1963]. Hubel and Wiesel found cells that they classified hierarchically as simple, complex and hypercomplex. Simple cells respond to edges, slits or lines. The edge, slit or line must be precisely located and oriented in the visual field to cause a given cell to fire at the maximum rate. Although location is not so critical for complex and hypercomplex cells, they have the added characteristic of responding maximally when the preferred stimulus is in motion in a direction perpendicular to its orientation. Many of these cells are also directionally selective in that they respond to motion in one direction but not to motion in the opposite direction.

In 1961, two years after the first report by Hubel and Wiesel, N. Stuart Sutherland, who is now at the University of Sussex, suggested that cortical cells of the kind described by the Harvard workers might underlie aftereffects of motion and orientation. His explanation, like the one we have described for afterimages, invoked the concept of neural fatigue. According to Sutherland, the perception of the orientation of a line would involve a kind of averaging of the activity of all the line detectors that respond to the line. If one looks at, say, a vertical line, the neurons most sensitive to verticalness are the most active and there is no overall bias due to the activity of cells sensitive to other orientations. The decision about the orientation of the line therefore corresponds to reality.

Now suppose the observer looks for some time at a line that is tilted 15 degrees clockwise. Line detectors maximally sensitive to the 15-degree line become fatigued, so that when the observer looks at the vertical line, the balance of activity is shifted counterclockwise away from the vertical. A similar process could underlie motion aftereffects.

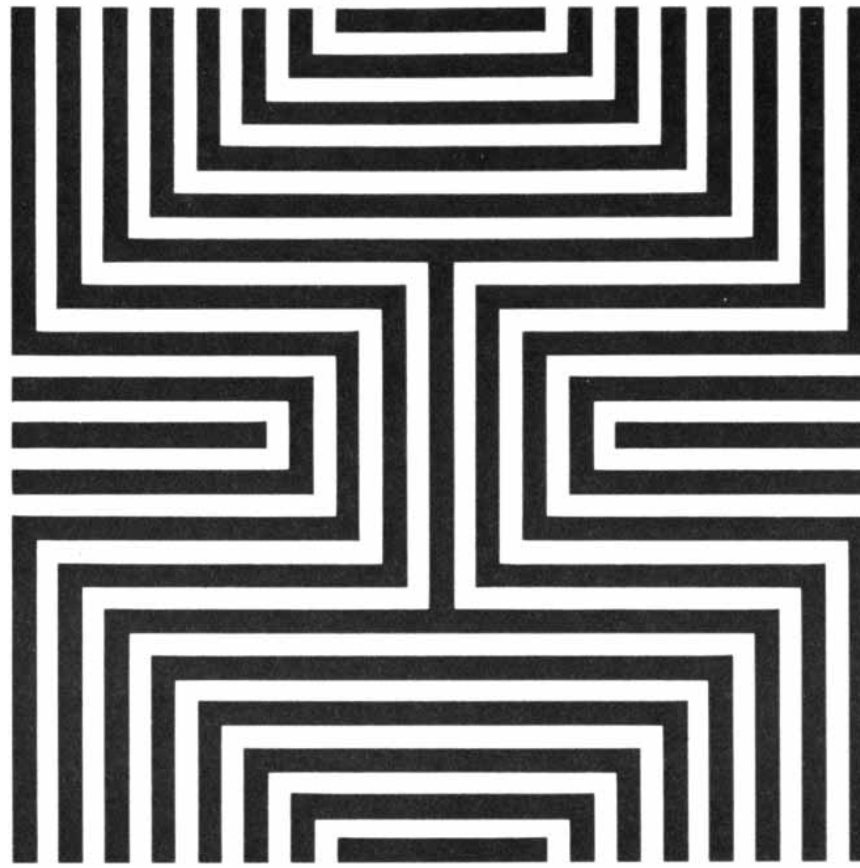
The recognition that single cells in the cat's brain are simultaneously sensitive to more than one specific feature of environmental stimuli, such as orientation and brightness, introduced the possibility of discovering aftereffects with multiple components. The possibility was first realized by Celeste McCollough of Oberlin College. She reasoned that human beings probably have line detectors similar to the ones found in cats and that since people, unlike cats, also have color vision it might not be unreasonable to suppose that human line detectors are specialized for color as well as for orientation. If they are, one might be able to demonstrate aftereffects that depend on both the orientation and the color of lines.

McCollough accomplished the dem-

onstration in the following way. Subjects looked at grids of horizontal blue and black lines alternating every few seconds with grids of vertical orange and black lines. After about 10 minutes they were shown grids of horizontal and of vertical white and black lines. The horizontal grids appeared to have a faint orange color and the vertical grids were tinged with blue. This result can be described as an orientation-contingent color aftereffect; it is generally known as the McCollough effect.

It is unlikely that the McCollough effect is retinal in origin. For one thing it is clear that the perceived colors are not simply complementary afterimages, since either color can be seen in the same retinal location, depending only on the orientation of the lines in the grid. Moreover, it is not necessary to gaze fixedly at the figures in order to get the McCollough effect.

Another aspect of the McCollough effect that differentiates it from simple afterimages is its extreme persistence. With an adaptation period of 10 or 15 minutes the effect may still be visible days or even weeks later. Because of these properties it is generally believed that the mechanisms responsible for the McCollough effect are localized in the visual cortex of the cerebrum. Three years after McCollough's discovery Hubel and Wiesel reported that the visual cortex of the monkey does in fact contain neurons sensitive to both the orientation and the color of a stimulus.



BLACK-AND-WHITE PATTERN, viewed in conjunction with grids on opposite page, produces the orientation-contingent color aftereffect. Such multiple-component aftereffects are called McCollough effects after Celeste McCollough of Oberlin College, who discovered them.

Other reports of contingent aftereffects have followed McCollough's work. Norva Hepler of McGill University and Charles F. Stromeyer and R. J. W. Mansfield of Harvard University independently discovered that color aftereffects can be made contingent on the direction of motion of a pattern. For example, if an observer alternately watches a spiral rotating clockwise in green light and counterclockwise in red light, a black-and-white spiral may subsequently appear pinkish if it is rotated clockwise and greenish if it is rotated counterclockwise.

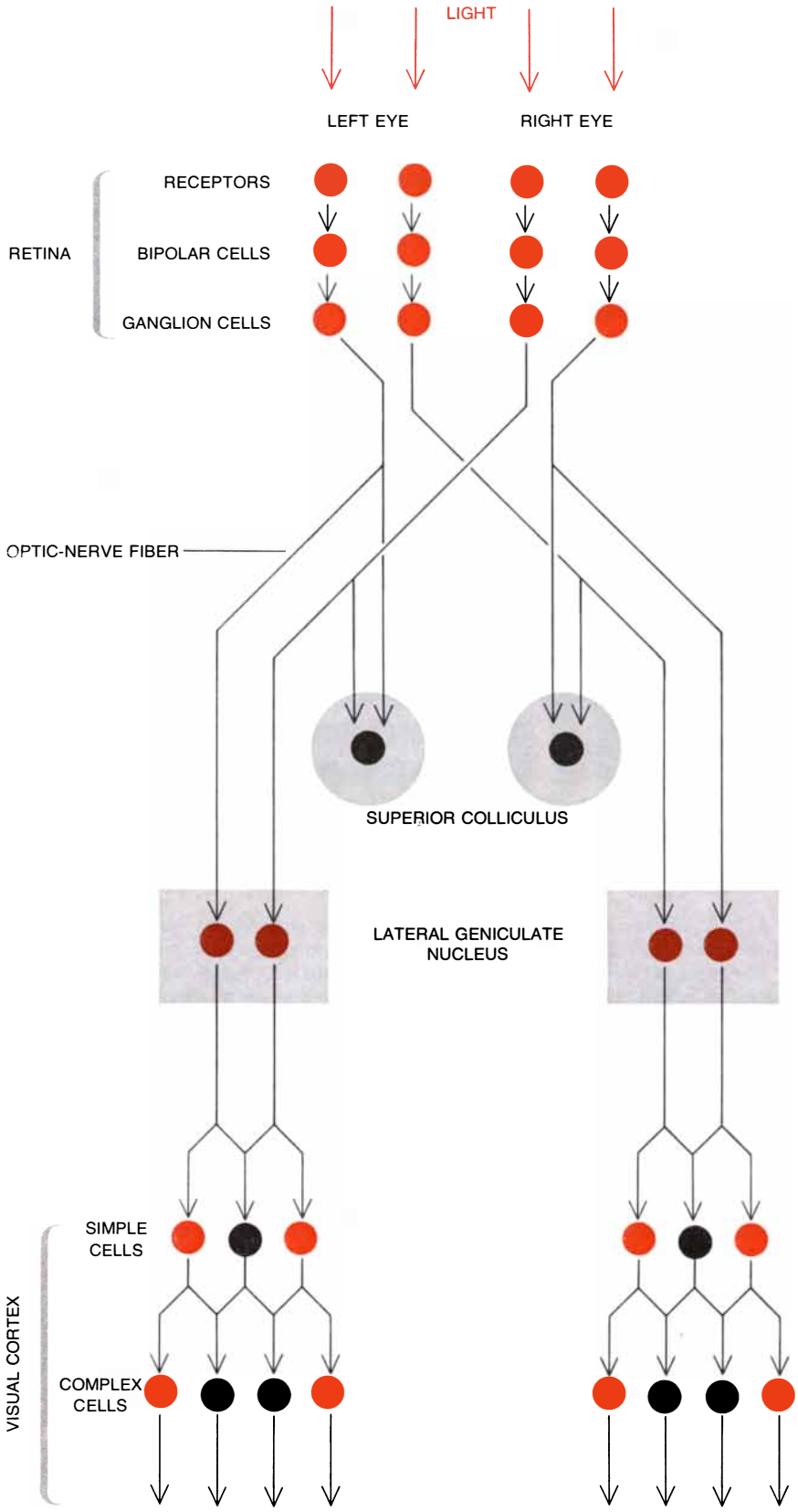
We and Victor F. Emerson, working at McGill, discovered that it is possible to induce the converse of this contingency. (The finding was also reported by Anstis and John E. W. Mayhew.) After watching a green clockwise spiral alternating with a red counterclockwise spiral observers report that a stationary spiral appears to move briefly counterclockwise when it is green and clockwise when it is red. This is a color-contingent motion aftereffect. Like the motion-contingent color aftereffect, it is long-lasting, that is, although it is brief for any one exposure to a colored spiral, it can reappear when the spiral is looked at again. Both the color-contingent motion aftereffect and the motion-contingent color aftereffect can reappear if an observer is shown the test patterns 24 hours after adaptation.

The evidence we have reviewed so far seems to support the view that aftereffects depend on the properties of feature detectors that bear a close functional resemblance to the neurons described by Hubel and Wiesel. Nevertheless, investigators in both neurophysiology and human perception have recently sought to prove the existence of detectors that respond to more integrated properties of the visual display. Indeed, some workers now believe the neurons studied by Hubel and Wiesel do not function simply as edge, slit or line detectors but also contribute to an analysis of the spatial frequencies (the spacing of more or less regularly repeating elements) in the total display. It has been found that individual neurons in the visual cortex of the cat respond selectively to sinusoidal gratings (parallel bars having a brightness that varies in a sinusoidal manner across the grating) only within a narrow range of spatial frequencies [see "Contrast and Spatial Frequency," by Fergus W. Campbell and Lamberto Maffei; SCIENTIFIC AMERICAN, November, 1974].

A number of aftereffects can be attributed to detectors of spatial frequency. For example, Colin Blakemore and Peter Sutton of the University of Cambridge discovered that if one looks at a striped pattern for some minutes and then views a grating with the same orientation but slightly narrower bars, the bars seem even narrower and more closely spaced than they really are. Conversely, broader bars seem broader [*see bottom illustration on page 48*].

The explanation proposed by Blakemore and Sutton was similar to the one advanced by Sutherland to explain tilt and motion aftereffects. They suggested that a grating of a particular frequency arouses activity in a subpopulation of frequency-detecting neurons. The distribution of activity is averaged to provide a perceptual impression of what the displayed frequency is. Preadaptation to some other spatial frequency would have depressed the activity of neurons sensitive to that frequency and so would skew the distribution away from the distribution normally evoked by the displayed pattern.

Color aftereffects can also be made contingent on spatial frequency. W. J. Lovegrove and Ray F. Over of the University of Queensland had subjects watch a vertical grating of one spatial frequency in red light alternating with a vertical grating of a different spatial frequency in green light. Afterward a black-and-white test grating of the first frequency appeared greenish and a grating of the second frequency appeared



VISUAL SYSTEM is depicted schematically to show the flow of information. The neurons, or nerve cells, represented in color are driven by only one eye, whereas the ones shown in black are driven by both eyes. Hence if an aftereffect that has been induced in one eye is observed to transfer to the other eye, one can infer that it is mediated by cells either in the visual cortex of the brain or in the superior colliculus. Afterimages, in contrast to aftereffects, do not transfer from one eye to the other, so that they evidently originate in early stages of visual processing.

pinkish. Color aftereffects occurred, however, only if the frequency of one grating was at least twice that of the other and if the frequency of at least one grating was higher than three cycles per degree of visual angle. Lovegrove and Over suggested that their results could be explained in terms of the adaptation of neural units tuned for both color and spatial frequency.

A useful way to check on the location in the visual system of the neurons responsible for aftereffects is to test for interactions of the eyes. For example, one can induce an aftereffect in one eye and then ask whether the observer sees it when he looks with the other eye. Neurons in the visual pathway from the retina to the visual cortex are driven by one eye up to and including the lateral geniculate nucleus. In the visual cortex some neurons are driven monocularly (by an input to one eye only) and others are driven binocularly (by an input to either eye). Most of the cells in the superior colliculus (another part of the visual-processing system) are driven binocularly. Hence if an aftereffect is observed to transfer from one eye to the other, one can infer that it is mediated by cells in either the visual cortex or the superior colliculus. Since neurons in the superior colliculus appear to be sensitive mainly to motion, however, their role (if they have one) would be confined to motion aftereffects.

It has generally been found that figural and motion aftereffects, unlike afterimages, do transfer from one eye to the other, although their strength is reduced in the process. These aftereffects are therefore probably mediated by both monocularly and binocularly driven neurons. In the eye that was exposed to the adapting pattern both kinds of neurons would mediate the effect. In the other eye, however, only the neurons driven binocularly would be involved, which accounts for the reduction in strength.

Contingent aftereffects where one of the components is color apparently do not transfer from one eye to the other. This finding suggested that they may be mediated by monocularly driven neurons. Some evidence indicates, however, that this hypothesis may not be altogether correct. Experiments conducted by T. R. Vidyasagar of the University of Manchester have indicated that orientation-contingent color aftereffects can involve neurons that require an input to both eyes. Such neurons are binocular, but they could not mediate an interocular transfer. It seems possible that other contingent aftereffects may also involve binocular neurons of this type.

Gerald M. Murch of Portland State University has demonstrated that the color and motion components of an af-

tereffect can be dissociated. He has also shown that the motion component transfers from one eye to the other and the color component does not. Murch's procedure involved an adaptation phase and a test phase. In the adaptation phase he presented to the right eye a spiral whose motion was alternated between clockwise and counterclockwise, and at the same time he presented to the left eye the contingent color, alternately red and green. In the test phase the observer looked at stationary red or green spirals with first one eye and then the other. The contingent aftereffect (clockwise movement of the green spiral and counterclockwise movement of the red one) was reported only when the observer used his left eye. The adaptation to motion thus transferred from one eye to the other but the information about the contingent colors did not.

Murch's elegant experiment raises a general question about the nature of contingent aftereffects. Until recently it had been widely assumed that they are due solely to the adaptation of "multiple duty" neurons tuned to the different components, such as color and orientation, that underlie the aftereffects. Murch and other workers have questioned this assumption, suggesting instead that the contingency may depend on associative connections between different classes of neurons, each type tuned to a single component of the visual experience. Although Murch's experiment does not rule out the participation of multiple-duty neurons in the mediation of contingent aftereffects, it does introduce the possibility that such aftereffects can also be mediated by associations among previously independent neurons.

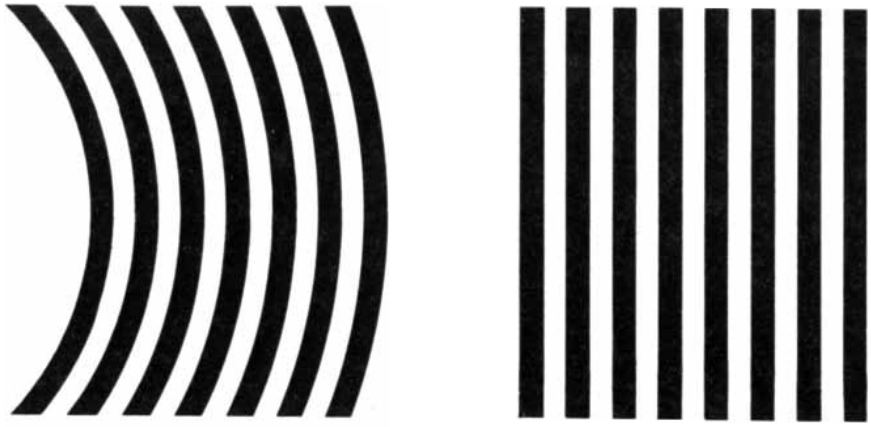
The possibility that contingent aftereffects may depend on the formation of associative connections rather than (or perhaps in addition to) fatigue has been suggested for another reason, namely the persistence of many contingent aftereffects. As we have mentioned, they can be detected days or even weeks after the adaptation period. We know of no neurophysiological evidence that fatigue or the adaptation of single neurons ever persists for such a long time.

Indeed, the persistence may not be confined to contingent aftereffects, although the question of whether or not an aftereffect is contingent is sometimes a fine point. Richard F. Masland of McGill showed that features of the spiral aftereffect can persist for as long as 24 hours. One of us (Favreau) has found that it may still be present a week later. The decrease in magnitude of the spiral aftereffect is rapid during the first few minutes, but thereafter the rate of decrease is markedly slower. For this reason Masland suggested that the aftereffect has two components: a rapidly decaying component directly due to the adaptation of motion detectors and a more slowly decaying, more persistent component caused by the conditioned adaptation of the detectors. In conditioned adaptation, although the motion detectors would not remain fatigued for the entire period during which the aftereffect persists, the spiral configuration, having become associated with fatigue, could cause the detectors to return to a state resembling fatigue.

SPIRAL AFTEREFFECT is caused by putting a spiral on a turntable and rotating it at $33\frac{1}{3}$ revolutions per minute. When the spiral is stopped, it seems to move in the other direction.

Although the concept of conditioned adaptation or fatigue could be useful in explaining the long-term persistence of negative aftereffects, it presents a stumbling block. If the various attributes of the inducing stimulus, such as spiral configuration and clockwise motion, become associated with one another, one

TILT AFTEREFFECT appears when one has looked steadily for about five minutes at the tilted lines. Thereafter lines that are actually vertical will seem to tilt in the opposite direction.



CURVE AFTEREFFECT results from looking at curved lines for 10 minutes, moving the eyes only along the central portion. The straight lines will then appear to curve the opposite way.

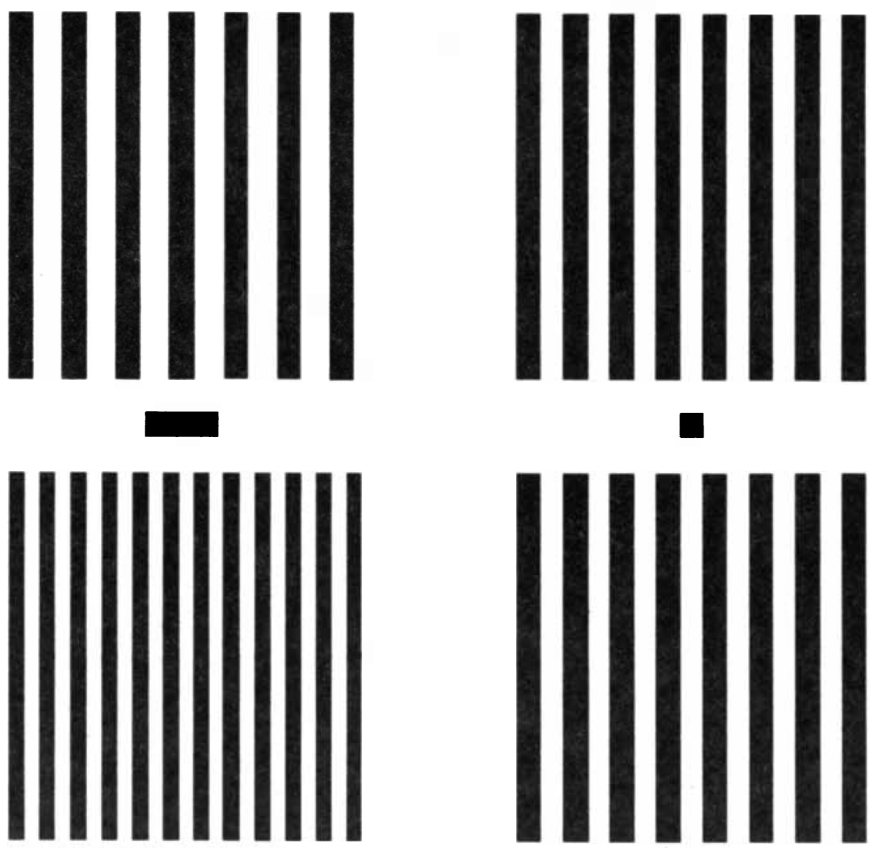
would expect to obtain positive aftereffects rather than negative ones. Thus, for example, a stationary spiral would appear to rotate in the direction in which the spiral was previously seen rotating and a colorless vertical grating employed to test for the McCollough effect would appear green if the vertical orientation had been paired with green. The striking feature of negative aftereffects, however, is that when two attributes are combined in a stimulus, one of them subsequently becomes associated with an opposite quality of the other (movement in the other direction, the complementary color and so on).

It is plausible that fatigue could become associated with aspects of the adapting stimulus, since it is known that the processes of fatigue start operating as soon as one looks at a stimulus. When one views something that is constantly moving, the perceived velocity decreases. When one looks at a colored surface, the color appears to become desaturated. (The reader can verify this relation by looking at one of the colored patches in the illustration on page 43. If half of the patch is obscured by a piece of gray paper that is removed after about 30 seconds, the part of the patch that was covered appears to be brighter than the part that was exposed.)

We have now examined two possible explanations of negative aftereffects: fatigue and conditioned fatigue. Possibly they both play a role. Masland's work on the spiral aftereffect showed that it has two components. One of us (Favreau) has conducted experiments that suggest a further dissociation of the short- and long-term components of this aftereffect. The simple aftereffect is observable immediately after one looks at a spiral, and it also decreases steadily in strength. The color-contingent spiral aftereffect is not seen immediately and does not reach full strength for several minutes. The finding suggests that during an exposure to spirals of alternating motion and colors, visual units sensitive to both directions of motion may become fatigued and hence prevent the rapid appearance of a motion aftereffect. As the fatigue wears off, the effects of mechanisms underlying the color contingency may be revealed.

If contingent aftereffects do depend on the formation of associative connections between visual units, the question arises of how such connections are established. One possibility is that information from different sets of feature-extracting neurons converges in a mutually interactive way at a higher level of visual processing. The interaction (between, say, color and motion) would be recorded by a relative adaptation across a bank of neurons at the higher level. Thereafter the activation of this system by either of the original sets of neurons could re-create the impression of adaptation in the other set, thereby yielding the appropriate negative aftereffect.

This account still relies on the notion of adaptation, or habituation, of neurons. These hypothetical neurons, however, are at least removed from the feature-analyzing neurons that have been studied intensively and have not been observed to exhibit long-term adaptation effects. Neurons of this kind, which store patterns of interaction by means of long-term habituation, may play a rather general role in learning and memory.



SPATIAL VARIATIONS can also cause aftereffects, apparently because certain neurons in the visual system are sensitive to spatial frequencies, that is, the spacing of more or less regular features of something one is looking at. One can obtain the aftereffect by first looking at the two sets of vertical bars at the left to determine whether they are the same. Then move your eyes back and forth along the horizontal bar between the two sets of vertical bars for about five minutes. When you shift your gaze to the horizontal bar between the vertical grids at the right, the spatial frequency of the grid at the top will appear to be higher than that of the grid at the bottom. If the illustration is turned upside down, the spatial relations will then reverse.

BBBT and other health products

N,N'-bis [*p*-butoxybenzylidene] -α,α'-bi-*p*-toluidine (BBBT) is a mesomorph, more popularly known as a "liquid crystal," a new addition to the long list of organic compounds that show interesting kinds of intermolecular association on the way from the solid to the ordinary isotropically liquid state as temperature rises. Beginning on p. 809 of the May, 1976 issue of *Analytical Chemistry*, workers at the National Cancer Institute tell how they prepared BBBT from a simpler EASTMAN Organic Chemical and why they have found BBBT better than any previously known substance when used as the stationary phase in gas-liquid chromatography for detecting and distinguishing geometric isomers of polycyclic aromatic hydrocarbons of interest as possible environmental carcinogens.

On May 14, 1976 we logged in our first inquiry from a scientist who wanted to try BBBT but preferred to buy it instead of spending his time making it. He and all others who need it can now order it from lab suppliers as EASTMAN Organic Chemical No. 15076.

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SCIENCE AND THE CITIZEN

The Nobel Prizes

The 1976 Nobel prizes in science were awarded to two physicians for discovering the origin and mechanisms of certain infectious diseases, to two physicists for the independent and simultaneous discovery of a new elementary particle, to a chemist for solving the bonding mechanisms and structures of boron compounds and to an economist for his studies of the role of money and of consumer income consumption in economic theory. Each of the four prizes this year is valued at about $160,000.

The prize in medicine was shared by Baruch S. Blumberg of the Institute for Cancer Research in Philadelphia and D. Carleton Gajdusek of the National Institute of Neurological Diseases and Stroke. In the early 1960's Blumberg studied some 100,000 blood samples taken from widely diverse populations—American Indians, Africans, Eskimos, East Asians and Pacific islanders—trying to discover how genetic variations influence susceptibility to disease, particularly hepatitis. In 1963 he discovered in the blood serum of an Australian aborigine a clue to the virus that causes one of the two forms of hepatitis. He found that the serum contained an antigen that reacted with an antibody in the serum of a patient with hemophilia. Evidently the patient had acquired the antibody from an unidentified blood donor in the course of one of numerous blood transfusions.

Subsequently Blumberg and his colleagues were able to show that the "Australia antigen" was part of the virus that causes the most severe form of hepatitis, hepatitis B. Recently Blumberg has found evidence that the virus can also cause primary liver cancer, which is rare in the U.S. but is a major health problem in some parts of the world. Although no way has yet been found to grow the virus in the laboratory, a vaccine against hepatitis B can be made with the serum from donors whose blood is rejected for transfusion because it gives a positive test for the Australia antigen. The vaccine is now being produced for testing by Merck & Co. If the vaccine is effective against hepatitis B, it could conceivably protect as well against the liver cancer the virus causes.

The investigation that earned Gajdusek his share of the award began nearly 20 years ago when he was traveling in Australia and heard about kuru, a usually fatal disease that afflicted the Fore people, a cannibalistic tribe in New Guinea. Gajdusek set up a research station in one of the Fore villages and obtained bodies of kuru victims for autopsy by trading axes and tobacco. He finally established that kuru was caused by a virus that attacks the central nervous system. The victims of the disease had acquired it through a ritual practice that involved eating the brain of the recently deceased. The kuru virus closely resembles another slow-acting virus that causes scrapie, a disease that destroys the nervous system in sheep. It is suspected that similar slow-acting viruses may be responsible for multiple sclerosis, Parkinsonism and other poorly understood neurological diseases.

The prize in physics was awarded to Burton Richter of Stanford University and to Samuel C. C. Ting of the Massachusetts Institute of Technology, each a leader of a large group of experimental physicists engaged in a search for new elementary particles. Richter's group conducted its experiments at the Stanford Linear Accelerator Center (SLAC) in California. Ting's group worked at the Brookhaven National Laboratory in New York. The new particle they found independently in November, 1974, called the psi particle by Richter and the *J* particle by Ting, was totally unpredicted by theory. Indeed, one leading theorist advised Ting that his proposed search would be fruitless because there were no new particles in the energy range Ting planned to explore. Ting decided to proceed anyway, since, he says, "I usually do not have much confidence in theoretical arguments."

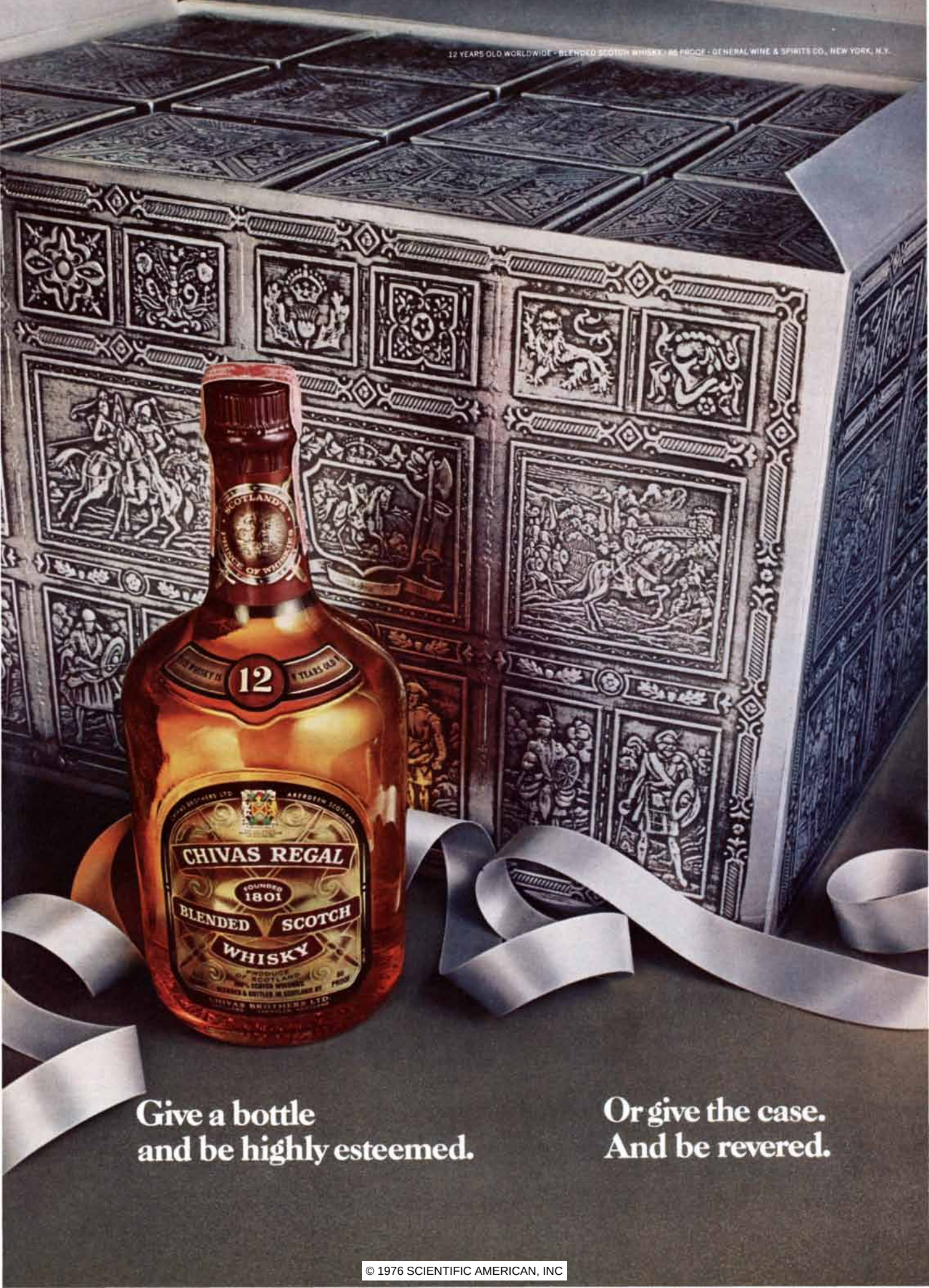
Beginning in the summer of 1972 Ting's group assembled a massive particle spectrometer involving a complex system of magnets and detectors adjacent to the Brookhaven 33-GeV (billion-electron-volt) synchrotron. The concrete shielding alone weighed 10,000 tons. The spectrometer was designed to search for long-lived neutral particles in the region of masses equivalent to energies between 1.5 and 5.5 GeV. It was assumed that the particle, if it existed, would decay into a pair of electrons and positrons whose energy would peak at some value corresponding to the mass of the parent particle. The detection equipment had to be sensitive enough to select one significant event out of a background of between a million and 100 million similar but nonsignificant events. The first positive results were obtained in August, 1974. By October, Ting had strong evidence for a new neutral particle with a mass of 3.1 GeV (about three times the mass of a proton).

Meanwhile, over nearly the same period beginning in 1973, Richter and his colleagues at SLAC had been assembling detectors to look for new particles that might be produced by collisions between positrons and electrons in the Stanford Positron-Electron Accelerating Ring (SPEAR). The ring stores and circulates counterrotating positrons and electrons injected with energies of up to 4.5 GeV by the Stanford two-mile linear accelerator. By October, 1974, Richter's group had obtained preliminary evidence for a new particle with a mass of 3.1 GeV. By Sunday, November 10, the evidence was conclusive. A paper describing what the Stanford team called the psi particle was drafted that evening.

The next morning there was a routine meeting of the SLAC scheduling committee of nine members, which advises SLAC on the acceptance of new proposals. Ting was one of the visiting members. Richter recalls that when he met Ting that morning, Ting said, "Burt, I have some interesting physics to tell you about." To which Richter replied, "Sam, I have some interesting physics to tell *you* about." This was the first either had heard of the other's exciting discovery. The two papers announcing the psi/*J* particle were published simultaneously within the week. To theorists the new particle and the subsequent discovery of still heavier particles in the same family (psi′, psi″ and psi‴) provide nearly conclusive evidence that the building blocks of hadrons (particles, such as the proton and various mesons, that "feel" the nuclear force) include a "charmed" quark in addition to the basic three quarks proposed some years ago (see "Quarks with Color and Flavor," by Sheldon Lee Glashow; SCIENTIFIC AMERICAN, October, 1975).

William N. Lipscomb was awarded the prize in chemistry primarily for studies begun at the University of Minnesota in the late 1940's and continued at Harvard University after 1959. Lipscomb set himself the task of determining the structure of boranes, compounds of boron and hydrogen, that had resisted earlier attempts at elucidation. The primary difficulty lay in understanding the bonding mechanism that produced compounds with such curious atomic ratios as B_2H_6, B_5H_9, B_5H_{11}, $B_{10}H_{14}$ and $B_{18}H_{22}$. Although such formulas superficially resemble those of some hydrocarbons, it was clear that boron and hydrogen atoms were not linked together by the typical covalent bond found in hydrocarbons. In that bond adjacent carbon atoms or a carbon atom and a hydrogen atom normally share two electrons. Thus the normal covalent bond is a "two-center" one.

By using X-ray-diffraction techniques to study single crystals of boranes at extremely low temperatures, Lipscomb found that the typical borane structure is based on a "three-center" bond in which a bonding pair of electrons is



shared equally by three atoms. The geometry of the three-center bond lends itself to borane structures that build up into precise and beautiful polyhedral patterns. Lipscomb and his co-workers have also applied quantum-mechanical calculations to determine (and in many cases predict) the stability and reactions of borane molecules under diverse conditions. In recent years Lipscomb has turned his attention to proteins, deciphering the three-dimensional structure of carboxypeptidase A, the largest globular protein yet to be elucidated with high resolution.

The prize in economic sciences was awarded to Milton Friedman of the University of Chicago for "his achievements in the fields of consumption analysis, monetary history and theory, and for his demonstration of the complexity of stabilization policy." A onetime adviser to Barry Goldwater and Richard Nixon, Friedman is widely recognized as the most conservative of the country's major economists and by far the most influential. He has advocated such things as the abolition of social security, the deregulation of industry and creation of a voucher system that would allow parents to choose their children's public schools. He has been strongly criticized for giving a recent series of lectures to bankers in Chile.

Friedman's major scholarly work is *A Monetary History of the United States, 1867–1960,* coauthored with Anna J. Schwartz, in which he develops the theory that the economic cycle is determined more by money supply and interest rates than by fiscal policy. His Chicago "monetarist school" expounds the doctrine that "money matters," or, more strongly, "only money matters." Friedman has argued, for example, that when the Federal Reserve Board reduced the nation's money supply in the 1930's, it turned what would have been no more than a recession into the Great Depression.

Molecular Medicine

Familial dysautonomia, a recessively inherited neurological disorder found in Jews of eastern or central European origin, is characterized by instability of the autonomic nervous system, impaired perception of pain, temperature and taste, absent overflow tears, diminished or absent deep tendon reflexes and the inability to coordinate voluntary muscular movements. Since the disease is hereditary, some molecular defect must be involved, but until recently its nature has been obscure. Now David C. Siggers and his collaborators at the Johns Hopkins University School of Medicine and Johns Hopkins Hospital and the Stanford University School of Medicine have presented evidence in *The New England Journal of Medicine* that an abnormality of nerve-growth factor, a hormonelike substance involved in the development of the nervous system, may be implicated in dysautonomia and related syndromes.

The existence of nerve-growth factor (NGF) has been known since 1952, when Rita Levi-Montalcini, who is now at Washington University, discovered that some mouse tumors release a protein substance that selectively enhances the growth and differentiation of two classes of nerve cells: embryonic sensory neurons during an early phase of their development and sympathetic neurons (peripheral nerve cells that secrete adrenalin) throughout their life cycle. The factor was subsequently found in large quantities in snake venoms and in mouse salivary glands, and in trace amounts in the blood and tissues of several mammals, including man. When a minute amount of NGF is added to an isolated sympathetic ganglion in a laboratory tissue culture, projections sprout in large numbers from the cell cluster, forming a halo of nerve fibers around it in six to 10 hours. Parasympathetic ganglia (composed of nerve cells that secrete acetylcholine), however, do not respond to NGF.

The marked differential effect of NGF on different cell populations comes more sharply into focus when

antibodies specific for purified mouse NGF, made in the blood of goats, rabbits or horses, are injected into newborn rodents. Such injections result in the selective destruction of nerve cells in sympathetic ganglia, giving rise to a spectrum of severe functional disorders. The similarity of the symptoms in laboratory animals given anti-NGF to those in human patients with familial dysautonomia first aroused the suspicion of Siggers and his collaborators that NGF might somehow be involved in the disease. To investigate the question they examined NGF from the blood of dysautonomic and normal subjects for differences in the structure and function of the molecule. Two functional assays—ability to produce sprouting from a sympathetic ganglion in vitro, and degree of binding to a membrane fraction of sympathetic nerve cells—gave similar results for both groups. When NGF levels were determined by measuring the amount of binding to radioactively labeled anti-NGF antibodies, however, the results showed a striking discrepancy: dysautonomics, compared with normal subjects, had a threefold increase in blood-serum levels of a substance immunologically equivalent to NGF.

The minute amounts of NGF in human blood are close to the lower limit of resolution of the functional assays, and Siggers and his collaborators warn that their results are not unequivocal. Nevertheless, the large discrepancy between the levels of NGF measured by functional criteria and those measured by antigenic criteria suggests an abnormality of NGF in dysautonomia. Siggers and his collaborators speculate that dysautonomics have high levels of a substance that is structurally similar to NGF (and hence is able to cross-react with the anti-NGF antibody) but that is physiologically inactive. This substance could well be a hypothetical precursor of NGF (analogous to proinsulin, the precursor of insulin) that might accumulate because of an abnormality in some step essential to its later processing. Alternatively the cross-reacting substance could be the result of a mutation in the gene coding for the NGF protein. The mutant NGF molecule would have a shape slightly different from that of the normal molecule and so would be biologically less active, perhaps causing the body to compensate by synthesizing more of it; in this way a higher amount of NGF antigen could result without a corresponding increase in biological activity. In both cases, however, the normal results of the functional assays are puzzling, since they would appear to be inimical to the development of disease.

The latter paradox makes it seem more likely that the elevated level of NGF antigen in dysautonomics is secondary to some other abnormality rather than being the primary molecular defect. This hypothesis, however, is in itself an advance. By finding such an elevation the authors have strengthened the notion that the origin of the dysautonomia lies somewhere within the scope of function influenced by NGF.

The Optical Telephone

A fundamental change that appears likely to be made in telephone technology within a few years involves the transmission of messages with light waves rather than electrical or radio waves. The reason is that the quantity of information that can be carried by a communication channel, such as a pair of telephone wires, rises with the frequency of the signal, and the frequency of light waves is roughly 1,000 times the frequency of the shortest radio waves. Bell Laboratories and the Western Electric Company are now making the first prolonged test of a prototype light-wave system at their joint facility in Atlanta. The results so far hold the promise that light-wave communication will be in wide use in metropolitan areas by the early 1980's and will be employed sooner than that in special applications.

The prototype system includes as the light source a tiny gallium aluminum arsenide laser that is turned on and off 44.7 million times per second by a modulator circuit. The signals travel a total of 40 miles by shuttling back and forth in a 2,100-foot cable carrying 144 optical fibers, thin glassy filaments consisting of doped silica. The filaments have an extremely high transparency, which is necessary to avoid excessive loss of the signal with distance. The experiment showed that the filaments will carry a signal for more than four miles before it is necessary to regenerate the light pulses with a repeater. At the receiving end of the cable the signal is picked up by a small photodetector that converts the light pulses into electrical signals that are compatible with conventional telephone equipment.

A cable of the size laid for the prototype system could carry some 50,000 messages at a time (672 in each pair of optical fibers). The first application envisioned by the Bell System for optical communication is the transmission of information between telephone switching systems in metropolitan areas where space in underground conduits is limited and where much of the information that is now transmitted is in digital, or pulsed, form and can be accommodated readily by a pulsed system.

Sweaty Palms

In the pseudoscientific procedure referred to as Kirlian photography a person typically places a finger, which has been wired to a high-voltage source, on a piece of photographic film that is separated by a dielectric layer from a second electrode in the same circuit. When an electric potential is applied between the finger and the isolated electrode, a photographic image is obtained that consists of an array of bright "streamers" seemingly emanating from the fingertip. The dominant source of energy responsible for the formation of the image appears to be a corona discharge: a low-current ionization phenomenon that takes place in the atmosphere at electric-field strengths below the threshold at which a spark can form.

The practice of Kirlian photography, developed primarily by a Russian electrician named Semyon D. Kirlian and his wife Valentina, has attracted considerable attention in recent years, owing largely to assertions by parapsychologists and others that variations in the structure and color of such photographic images can be related in some way to changes in the physiological, psychological or "psychic" states of the subject. An exhaustive series of tests of the Kirlian technique has now been conducted by a multidisciplinary team of investigators "to determine to what extent observed image modulation can be explained by gaseous discharge processes and whether other processes contribute to the resultant image." The general conclusion of the study is that "a principal determinant of the form and color of Kirlian photographs of human subjects" is moisture, presumably a product of sweaty palms.

The results of the new study were reported in *Science* by the three principal investigators: John O. Pehek and David L. Faust, both of the department of physics and atmospheric science at Drexel University, and Harry J. Kyler, a psychologist on the faculty of Villanova University. Support for their work was provided by the Advanced Research Projects Agency of the Department of Defense.

In a summary of their findings Pehek, Faust and Kyler state that "photographic images obtained by the Kirlian technique are principally a record of corona activity during an exposure interval. Most of the variations in the images of the corona of a living subject who is in contact with the photographic film can be accounted for by the presence of moisture on or within the subject's surface. During exposure, moisture is transferred from the subject to the emulsion surface of the photographic film and causes an alteration of the electric charge pattern on the film, hence the electric field at the surface of the subject. As a result, large variations in the density of corona images, corona streamer trajectories, and image coloration can be brought about."

In the future, the investigators suggest, the technique (which they prefer to call corona-discharge photography) "may be useful in the detection and quantification of moisture in animate and inanimate specimens through the

orderly modulation of the image due to various levels of moisture."

The Floods of Mars

One of the most exciting discoveries made by the spacecraft *Mariner 9* as it traveled in orbit around Mars in 1972 was evidence of abundant surface erosion resembling channels carved by torrents of running water on the earth. No fewer than 24 major channels—several kilometers wide, as much as a kilometer deep and hundreds of kilometers long—were located in the equatorial and middle latitudes of the planet. Both their fresh appearance and the apparent rarity of meteorite craters superposed on them led analysts of the Mariner imagery to the preliminary conclusion that fluvial erosion had been a feature of the Martian environment within the past few hundred million years or perhaps even more recently.

Writing in *Journal of Geophysical Research,* Michael C. Malin of the Jet Propulsion Laboratory of the California Institute of Technology now reports that a more refined study of craters and other features superposed on several of the channels (*see illustration below*), together with a recalculation of the probable rate of past meteorite impacts on the Martian surface, has radically changed the estimated age of the Martian fluvial features. Far from being merely hundreds of million years old, they appear to be among the older features of the Martian surface. They were evidently formed during the "terminal bombardment" of Mars early in the history of the solar system some four billion years ago.

Channel on Mars 700 kilometers long appears in this **Mariner 9** *mosaic. Note craters in channel*

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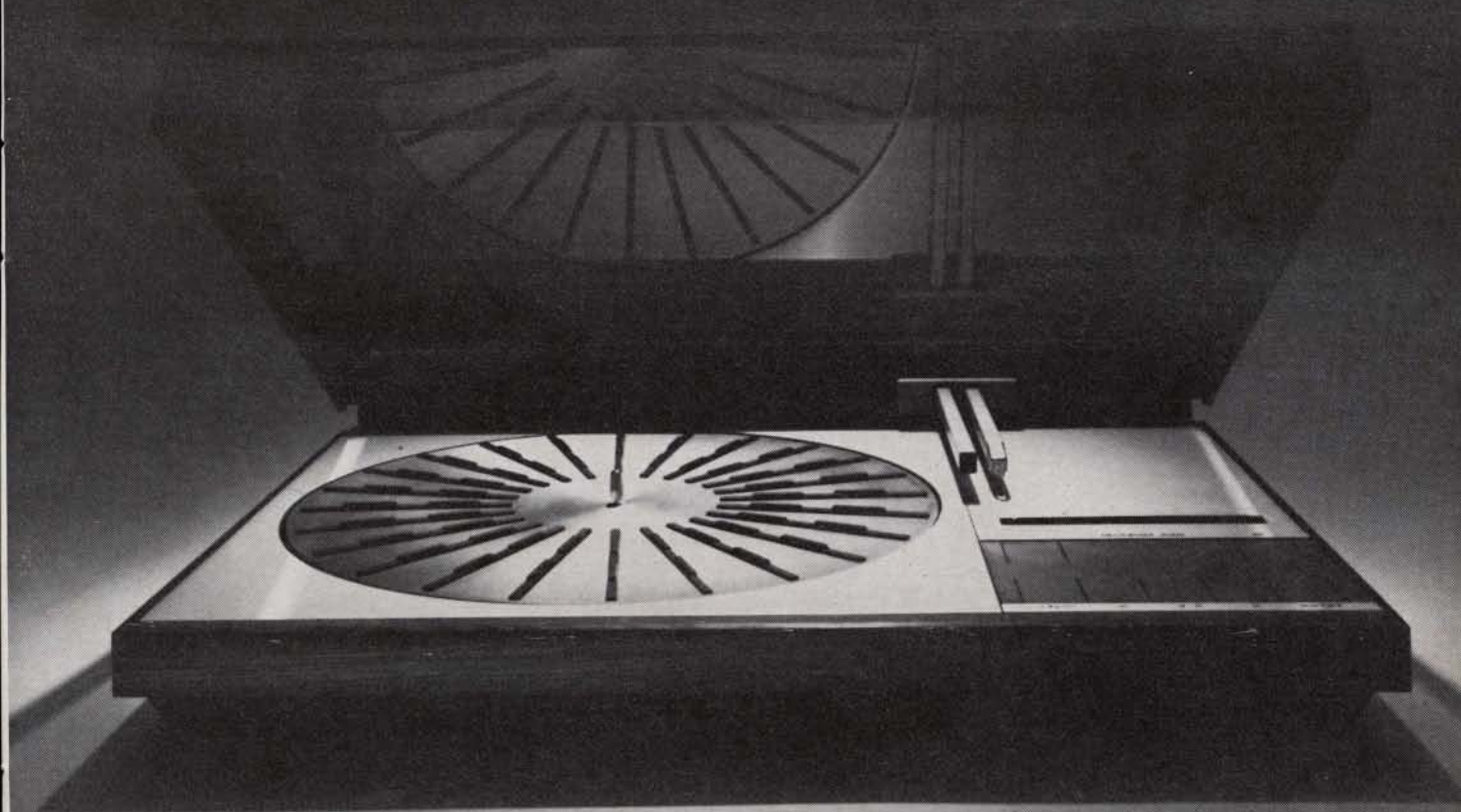

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Superfluid Helium 3

At a temperature a few thousandths of a degree above absolute zero this isotope of helium becomes able to flow through tiny pores without friction and exhibits bizarre magnetic effects

by N. David Mermin and David M. Lee

One of the less publicized frontiers of physical science lies in the realm of ultralow temperatures. This frontier opened up in 1911, when the first liquefaction of gaseous helium made it possible to achieve temperatures as low as a few degrees Kelvin (degrees Celsius above absolute zero). Today cryogenic techniques have progressed to the point where the properties of matter can be studied down to temperatures within a few thousandths of a degree above absolute zero.

There is a powerful incentive for performing such experiments. The behavior of matter is governed by the fundamental system of physical laws known as the quantum theory. Although all matter is subject to the laws of the quantum theory, ordinarily those laws are most strikingly manifested only on the microscopic scale of atoms and their constituent particles. Quantum effects are also displayed in the behavior of bulk matter, but the most spectacular and most interesting of such effects are obscured or even completely obliterated by the random thermal agitation of the atoms. Every advance in cryogenic techniques that lowers the range of accessible temperatures by another factor of 10 pulls back the curtains around still another level of bulk quantum behavior, often with quite unpredictable scientific and technological benefits.

The phenomenon known as superfluidity is probably the most spectacular example of quantum behavior in bulk matter that research at low temperatures has yet uncovered. Superfluidity is displayed within a few degrees of absolute zero by helium 4, the liquid form of the most abundant isotope of helium, the isotope with mass number 4. Under the name of superconductivity, superfluidity is also displayed by the conduction electrons in a great many metals and alloys, at temperatures that depend on the particular material but that are never more than about 25 degrees above absolute zero.

Superfluids contradict all intuition about how matter ought to behave. A superfluid can move in apparent defiance of the ordinary laws of friction, flowing effortlessly past obstructions sufficient to retard or entirely block the flow of a normal liquid. Superfluids can establish persistent circulatory currents that show little if any tendency to die away. When a vessel containing superfluid helium 4 is slowly rotated, the liquid may refuse to participate fully in the rotation. In a somewhat similar display of abnormal behavior the electron fluid in a superconducting metal may refuse to allow an external magnetic field to penetrate the metal. When the field is applied, the electrons, which carry an electric charge, produce whatever electric currents are required to generate an opposing field of the same strength as the applied one. The external field is canceled by this internal one and is therefore unable to penetrate the superconducting medium.

Until a few years ago superfluidity had been observed only in helium 4 and in superconductors. In 1971, however, a third form of superfluidity was discovered in liquid helium 3, the lighter and much rarer of the two nonradioactive helium isotopes. Since two isotopes of the same element ordinarily have quite similar properties, this might not seem a significant discovery. The two helium isotopes, however, are exceptions to the rule: their solid and liquid forms differ strikingly in almost all properties. Indeed, from the mid-1930's to the mid-1950's there was good reason to believe helium 3 could not become a superfluid, and it is now known that the mechanism for superfluidity in helium 3 is very different from that in helium 4.

In fact, the recent discovery of superfluidity in helium 3 has furnished us with a spectacularly different superfluid. Although the two helium superfluids share many characteristic superfluid flow properties, to bring about superfluidity in helium 3 requires a temperature almost 1,000 times lower than that needed to do so in helium 4. Where liquid helium 4 has one normal phase and one superfluid phase, helium 3 has a normal phase and three distinct superfluid phases. The helium-3 superfluids are magnetic. Furthermore, the superfluid phases of helium 3 are inherently anisotropic: measurements of their properties made in one direction can give quite different results from the same measurements made in other directions. These curious phenomena, like those seen in superfluid helium 4 and in superconductors, are all related to direct macroscopic manifestations of the quantum theory. Indeed, the quantum theory must be invoked even to explain the sizable differences between the two normal helium liquids, and for that matter to explain why they are liquid at all.

The Two Helium Isotopes

The helium isotopes are unique among all known liquids in refusing to freeze at ordinary pressure no matter how low the temperature; in principle they could be cooled all the way to absolute zero and still remain liquid. Solid helium can be formed only by cooling the liquid under pressure.

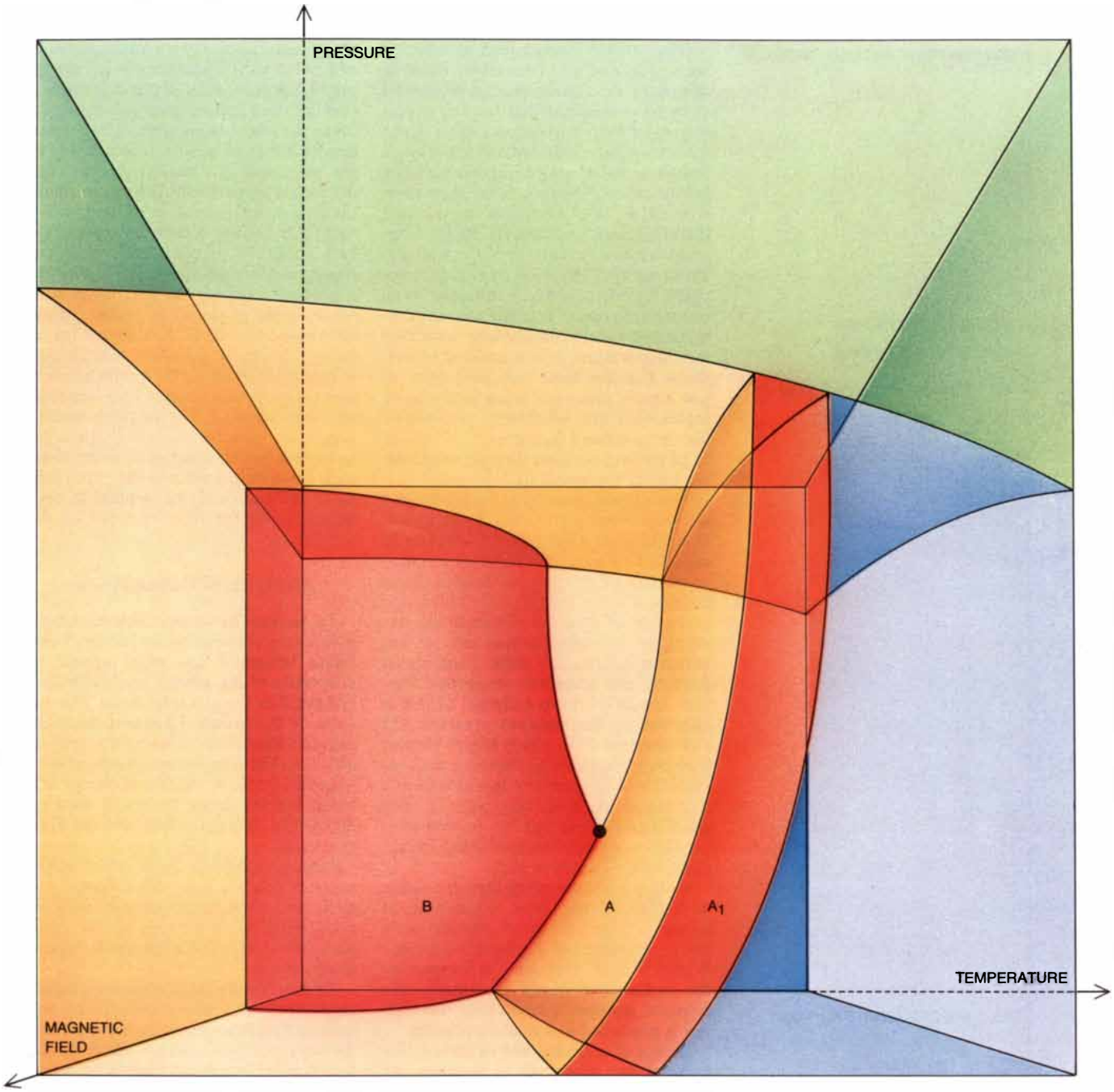
Cooling a substance reduces the average kinetic energy of its atoms or molecules; if the temperature is made low enough, the molecules lack the kinetic energy needed to overcome the intermolecular forces tending to bind them rigidly together. The molecules then lose their mobility and are confined to fixed positions: the substance becomes solid.

The failure of helium to freeze is due in part to the feebleness of the forces between its atoms. Helium is one of the inert or noble gases, the group of elements that also includes neon, argon, krypton and xenon. The interatomic forces in all these elements are exceptionally weak. Yet all but helium do freeze without the application of pressure if the temperature is low enough.

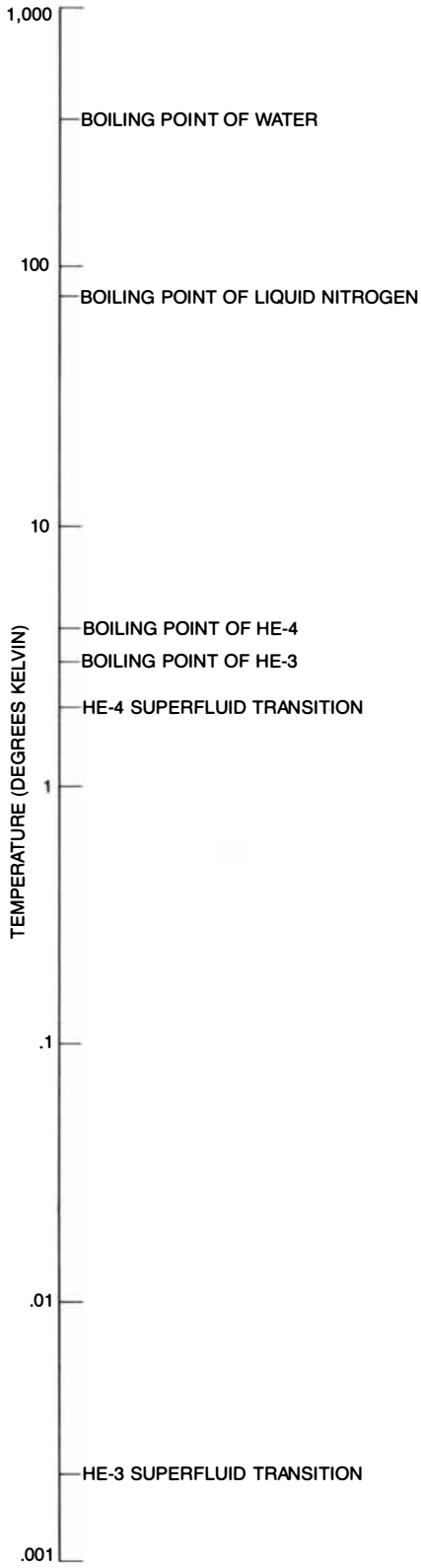
The failure of helium to solidify is perhaps the simplest way in which this extraordinary substance reveals the

laws of the quantum theory at work. In liquid helium, no matter how low the temperature, the atoms retain enough kinetic energy to overcome the attractive interatomic forces. This blatantly contradicts the classical (that is, pre-quantum-theoretical) view that at absolute zero the average kinetic energy is necessarily zero, so that the atoms sit motionless at fixed positions.

According to the quantum theory, this prediction is not precisely correct because it conflicts with the uncertainty principle, which states that the position and the momentum of a particle cannot be simultaneously specified with unlimited accuracy. In particular, if the position of an atom is rather precisely known, as it is in a solid, then the momentum or the kinetic energy of the atom must be uncertain by some small



FIVE PHASES OF HELIUM 3 (in addition to the gas phase) are found at the temperatures, pressures and magnetic-field strengths given in this three-dimensional graph. They are the normal liquid phase, three superfluid phases and the solid phase. Regions corresponding to the different phases are separated by surfaces. For example, if at high pressures (near the top of the liquid region) the temperature is reduced, a point representing the system passes first through a surface marking the transition between the normal liquid and the superfluid phase designated A_1; further cooling brings another transition to the superfluid phase A. If the magnetic field is reduced to zero, the A_1 phase is no longer present. Further cooling from the A phase reveals a third superfluid phase, B. The black dot at the back of the diagram where all three superfluid surfaces intersect is known as the polycritical point. Below the polycritical pressure superfluid phase B can be entered directly from normal phase in zero magnetic field.



TRANSITION TEMPERATURES for liquid-vapor phase changes in helium are the lowest of those for all the elements; at the boiling point of helium all other substances are frozen. Superfluid transition temperature of helium 3 is roughly 1,000 times lower than that of helium 4. The temperatures are on the Kelvin scale, in which absolute zero (−273.15 degrees Celsius) is taken to be zero degrees.

but finite amount. Conversely, a particle cannot have exactly zero kinetic energy and at the same time occupy a definite position. In the well-ordered crystalline array of the solid state the position of an atom is specified with great precision, and so the kinetic energy cannot be precisely zero. Even at absolute zero the atoms retain a certain "zero-point kinetic energy" and are therefore not altogether stationary.

Other things being equal, an object's zero-point energy increases as its mass decreases. Zero-point motion is so small as to be inconsequential for any object of greater than microscopic mass. Even the zero-point motion of a single atom is generally not of major importance. The helium atom, however, is the least massive of all the noble-gas atoms and therefore has a relatively large zero-point motion. Except at high pressures the combined effect of this large zero-point motion and the extremely weak interatomic forces is to prevent the formation of a stable solid phase, whatever the temperature. It is a curious coincidence that the same two properties of low atomic mass and weak interatomic forces that are ultimately responsible for the profound importance of helium to physicists are also directly responsible for its usefulness in balloons.

Quantum-mechanical effects not only are responsible for the instability of solid helium but also must be invoked to explain why even the simplest physical properties of the isotopes helium 3 and helium 4 differ significantly. With the exception of their atomic mass the isotopes of a single element are all but indistinguishable in their commonest physical and chemical properties. Perhaps the best-known example of this is afforded by the isotopes uranium 235 and uranium 238, which are so similar that merely separating them requires heroic efforts. Mixtures of liquid helium 3 and helium 4, in striking contrast, can spontaneously separate at certain temperatures, the two isotopes being immiscible, like oil and vinegar.

In nature almost all helium is helium 4; helium 3 has been obtainable in amounts large enough to provide more than a few drops of the liquid only since World War II. Helium 3 is formed by the radioactive decay of tritium, the heaviest isotope of hydrogen; the tritium is produced in a nuclear reactor.

Atoms of helium 3 and helium 4, like those of any other pair of isotopes, are almost identical in structure apart from the tiny central nucleus. Except for the nucleus each atom consists of a cloud of negative electric charge generated by two electrons, and for two isotopes of the same element these electron clouds are virtually indistinguishable in size and shape. In general two isotopes of the same element are so similar because most of the familiar physical and chemical properties of an element are determined entirely by its electronic structure. The chemical inertness of both helium 3 and helium 4 is one example of such similarity, but in almost all other respects the liquid forms of the two isotopes are surprisingly different.

The disparate behavior of the two isotopes is surprising because the only significant difference between them lies in the nuclei of the atoms. Helium 4 has two protons and two neutrons in its nucleus; helium 3 has two protons but only one neutron. If quantum effects are ignored, the only result of this difference is that helium 3 is the lighter substance, its mass per atom being about 25 percent less than that of helium 4. According to the principles of classical physics, this difference in mass should have no effect on the thermal properties of the two liquids. Yet helium 3 boils at a temperature about 25 percent lower than the boiling point of helium 4, and it requires a pressure roughly 25 percent greater for its solid phase to be stable. These discrepancies can be accounted for in large measure by the effect of the atomic-mass difference on the quantum zero-point energy. Since helium 3 is less massive than helium 4, its zero-point motion is greater. Therefore helium-3 atoms require less thermal energy in order to escape from the liquid into the vapor and more pressure must be applied to confine them to the rigid network of the solid state.

Properties of Helium Nuclei

To account for most of the remaining differences between liquid helium 3 and liquid helium 4 one must appeal to properties of the atomic nucleus rather less familiar than its total mass. The nucleus of the helium-3 atom spins on its axis at a fixed and permanently unalterable rate, like a gyroscope provided with a specified dose of rotational energy and freed forever from frictional slowing down. The nucleus of helium 4 does not spin at all.

Closely related to the presence or absence of nuclear spin, the helium-3 nucleus is a permanent magnet, with its poles lying along the axis of spin rotation. The nucleus of a helium-4 atom is nonmagnetic.

To describe the most important difference between the nuclei of helium 3 and helium 4 we must examine more closely the way particles are described by the quantum theory. According to the quantum theory, properties are allotted to particles and atoms only in discrete units, or quanta. Electric charge is a familiar example: in all observed particles and systems of particles its magnitude is invariably some integral multiple of the electric charge of an electron or a proton. This fact can be conveniently expressed by assigning every particle an electric-charge quantum number, which simply gives the magnitude of that parti-

cle's charge and can assume only the discrete values observed.

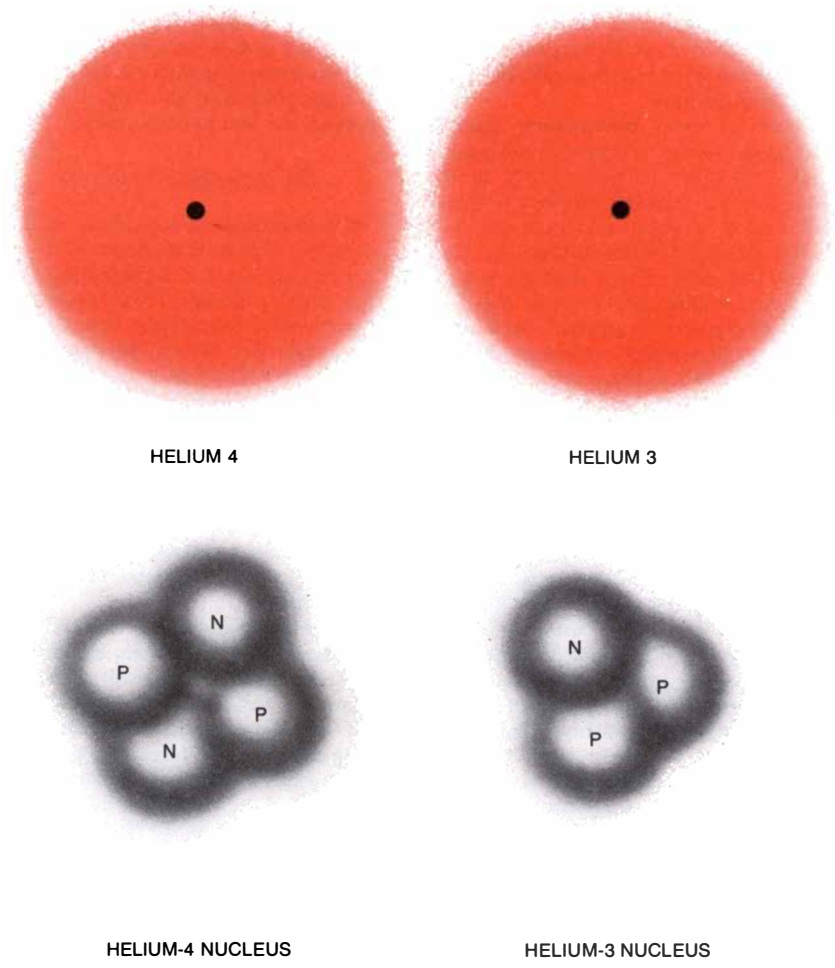
A less familiar and rather more startling example is the fixed and permanently unalterable rate at which spinning particles do their spinning. These rates are also confined to a set of discrete possible values, and the value that characterizes the spin of a given type of particle is as permanent a property of that particle as its electric charge.

The charge and spin of a particle are examples of quantum numbers with a single definite value that is characteristic of that species of particle. There are other quantum numbers, however, that can have a range of discrete values for a given particle. These quantum numbers specify the motion of the particle as a whole. Their values give information about the position or momentum of the particle.

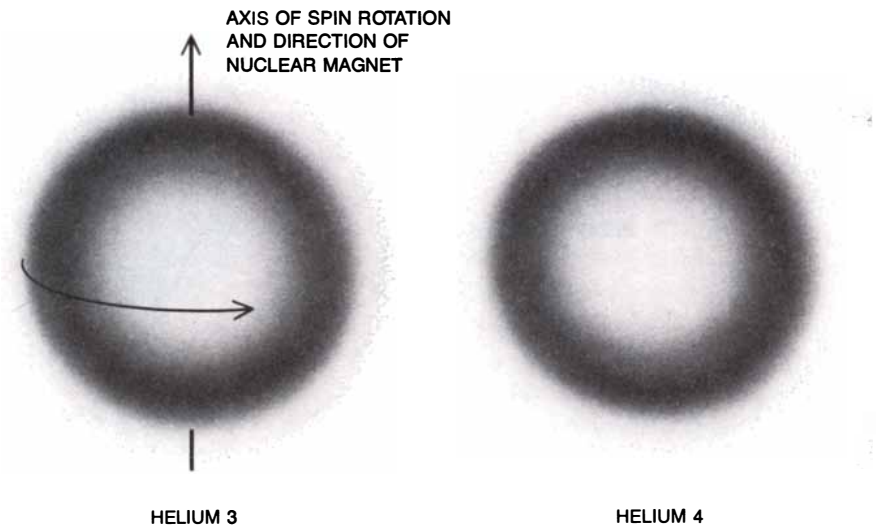
All the information it is possible to collect about what a particle is doing at any moment can be expressed by listing the values of all the particle's quantum numbers. Such a list of quantum numbers is said to define the state of the particle. A specification of a particle's state contains everything it is possible to say about the particle, including (within the limits set by the uncertainty principle) information about its position, its momentum and its kinetic energy.

In describing liquid helium 3 or liquid helium 4 or in describing the conduction electrons in a superconducting metal one is studying the behavior of large groups of identical particles. There is a class of elementary particles known as fermions, of which electrons, protons and neutrons are the most familiar and important examples, whose behavior in the aggregate is limited by the rule that no two fermions of the same type can be in precisely the same state. Given two electrons, for example, at least one of their quantum numbers must differ. No two fermions can behave exactly the same way. The application of this law to the orbits of electrons in atoms is fundamental to the theoretical explanation of the periodic table of the elements, but it also comes into play in many less familiar contexts and is of fundamental importance in understanding the difference in the properties of liquid helium 3 and liquid helium 4.

Not all elementary particles are fermions. There is a second class of particles called bosons, of which photons and pi mesons are examples. Although two fermions are prohibited from being in the same state, for bosons there is no equivalent principle of segregation. Bosons can be brought together in a single state in unlimited numbers. Indeed, under certain conditions a significant fraction of all the bosons in a large system of particles can occupy precisely the same quantum state. This bunching of bosons into the same quantum state is known as Bose-Einstein condensation. A collec-



ELECTRONIC STRUCTURES OF HELIUM ISOTOPES are almost precisely the same. The atoms of both helium 4 and helium 3 have two electrons, which form a spherical cloud of negative electric charge surrounding the nucleus (*top*). The two atoms differ significantly only in their nuclei, which are about 100,000 times smaller in diameter than the surrounding electron clouds. The helium-4 nucleus consists of two protons and two neutrons; the helium-3 nucleus has two protons but only one neutron (*greatly enlarged at bottom*). The physical and chemical properties of all other materials are determined almost entirely by the electronic structure of their atoms, but in helium the differences in nuclear structure give rise to many pronounced differences in behavior of both the liquid and the solid forms of the two isotopes.



NUCLEAR PROPERTIES of helium 3 and helium 4 differ. The helium-3 nucleus spins like a gyroscope and behaves magnetically as if it were a permanent bar magnet oriented along the axis of spin rotation. The vertical arrow indicates the direction of a magnetic pole; the equatorial arrow indicates the spin. The helium-4 nucleus possesses neither spin nor magnetism.

tion of bosons may or may not be Bose-Einstein condensed. For a system of fermions, however, such condensation is strictly prohibited.

Every known elementary particle (and according to current theoretical views, all those particles yet to be discovered or invented) is either a boson or a fermion. Nuclei or atoms (such as those of either helium isotope) are composite particles. Every nucleus is composed of elementary protons and neutrons, and every atom has in addition a cloud of elementary electrons surrounding its nucleus. Atoms are hence composed of three types of elementary particles, all of which are fermions.

The aggregate behavior of identical composite particles made out of two or more fermions is subject to the same restrictions as the behavior of elementary particles. Whether such composite particles are bosons or fermions is determined by a very simple rule: Particles composed of an odd number of fermions (of which a single fermion is the simplest example) behave like fermions, whereas particles composed of an even number of fermions behave like bosons. Thus helium 4, consisting of two electrons bound to a nucleus of two protons and two neutrons, is a boson because it is composed of six fermions, whereas helium 3, with one less neutron in its nucleus, is composed of only five fermions and is therefore itself a fermion. It is this arcane distinction that leads to the most profound of all the differences between the two helium liquids.

The Superfluid Transition

Manifestations of superfluid behavior in helium 4 were first observed in 1911 shortly after the first liquefaction of helium, and by the late 1930's most of the characteristic superfluid behavior had been observed. When the temperature of liquid helium 4 falls below 2.17 degrees Kelvin there is a sudden and discontinuous change in its properties. Below this transition temperature liquid helium 4 abruptly becomes a perfect conductor of heat, and it acquires the ability to leak with frictionless ease through minute cracks and pores that are completely impenetrable at higher temperatures.

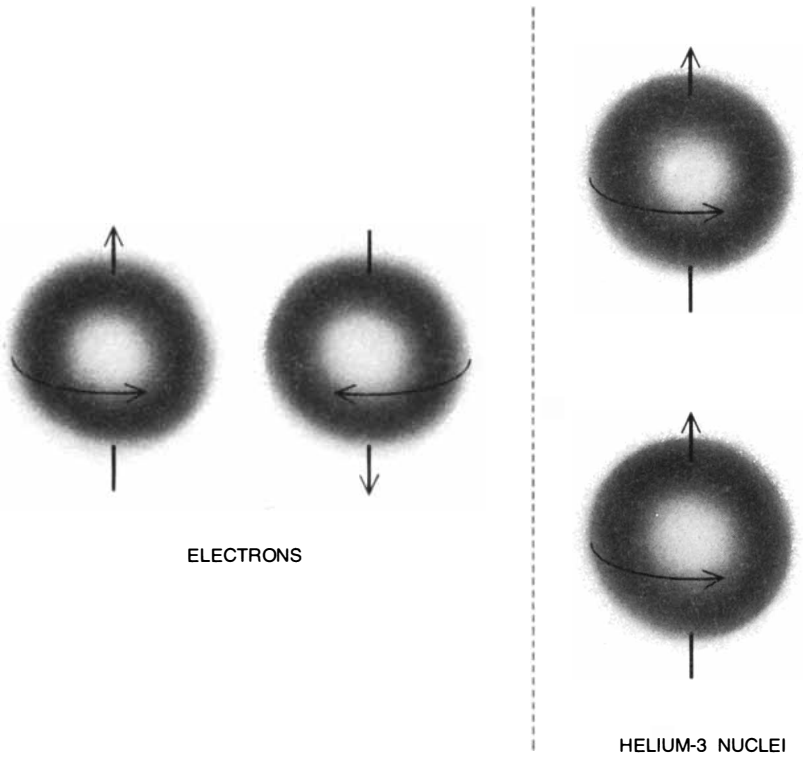
It was suggested in the 1930's that the superfluid transition in liquid helium 4 might be related to Bose-Einstein condensation, and it was recognized that if that were the case, then liquid helium 3, being composed of fermions, should not have a superfluid phase. The acquisition of helium 3 in quantities large enough for studies of the liquid phase was therefore eagerly awaited. In the 1950's it was established that no transition to a superfluid took place in helium 3 anywhere near 2.2 degrees. Subsequent experiments revealed that helium 3 could be cooled to temperatures below a hundredth of a degree without showing the slightest signs of superfluidity. These findings were taken as evidence that Bose-Einstein condensation does play a vital role in the superfluidity of helium 4, and today opinion is virtually unanimous that superfluid helium 4 is a liquid that has undergone Bose-Einstein condensation. The subsequent discovery of superfluidity in helium 3 at a few thousandths of a degree above absolute zero has not shaken that conviction. The mechanism underlying this superfluidity is quite different.

To indicate why Bose-Einstein condensation might lead to the characteristic superfluid properties of helium 4, it may help to consider an analogy with a more familiar system in which quantum-mechanical effects influence the bulk properties of matter. When André-Marie Ampère proposed in the 19th century that the magnetism of permanent magnets might arise from the flow of persistent microscopic electric currents, it was objected that such currents would rapidly dissipate their energy into heat and therefore cease. Ampère boldly ignored this difficulty, and his view was eventually vindicated by the quantum theory. Since physical properties on the atomic scale can vary only by discrete amounts, the gradual and continuous erosion of an atomic current by friction is impossible. In the realm of individual atoms, where properties are specified by discrete quantum numbers, things do not wear out; they either remain perfectly unaltered or are abruptly transformed into different things. If, as is often the case, there are reasons why none of a set of discrete alternative states is allowed, then no change whatever can occur.

This characteristic discontinuity and rigidity of atomic processes is indiscernible in ordinary bulk matter because the number of atoms it contains is so vast that although every atom obeys quantum laws, the combined effect of their discontinuous behavior is indistinguishable from perfect continuity. In a permanent magnet, however, the microscopic atomic currents described by Ampère are all flowing in such a way as to reinforce one another.

Similarly, in a system that is Bose-Einstein condensed, an appreciable fraction of all the atoms behave as if they were in precisely the same quantum-mechanical state, and as a result their motions are highly correlated. They are, as it were, marching in lockstep and can therefore reinforce one another's characteristic quantum properties, which can then be observed in the macroscopic behavior of the system.

The frictionless flow of superfluid he-



BOUND PAIRS OF FERMIONS are the condensed entities in superconductors and in superfluid helium 3. Superconductivity appears in a metal when the temperature falls low enough for the electrons to form bound pairs under the influence of a weak attractive force. In a like manner superfluidity appears in liquid helium 3 when pairs of atoms become bound together. In a bound electron pair in a superconductor the elementary magnets oppose each other, and the pair has no net intrinsic magnetism. The electrons also spin in opposite directions. The bound pairs of helium-3 atoms are quite different. The magnets reinforce each other, and as a result the pair possesses a net magnetism. Helium-3 nuclei also have same direction of spin.

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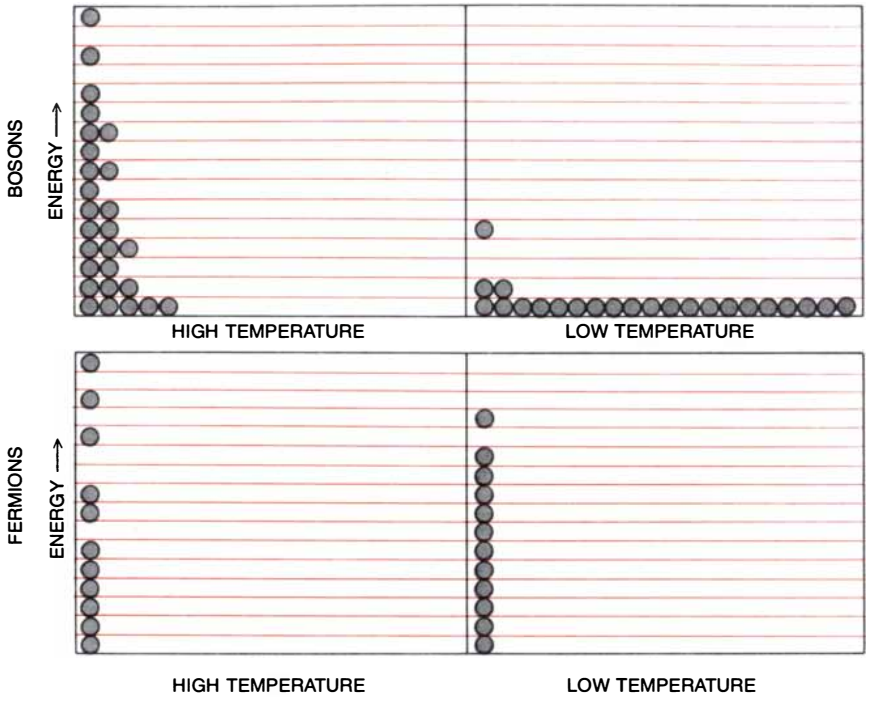

COLLECTION OF BOSONS is subject to quantum laws different from those that apply to a collection of fermions. Any number of bosons can have exactly the same set of quantum numbers, and at very low temperatures it is possible for an appreciable fraction of them to be in precisely the same state. Fermions obey a different rule: Only one fermion can have a given set of quantum numbers, so that it is never possible to have more than one fermion in a given state. In one simple model these rules lead to the following distinct kinds of behavior. At high temperatures the bosons are distributed over many states, which may or may not be occupied by more than a single boson. At low temperatures only the states of lowest energy are occupied appreciably, and number of bosons in state of lowest energy may actually be comparable to total number of bosons in system. Since only one fermion can occupy a given state, all that can happen as temperature drops is that occupied states settle down to group lying lowest in energy. Energy cannot be further reduced by assigning more than one fermion to lowest states.

	HELIUM 4	HELIUM 3	SUPERCONDUCTORS
TRANSITION TEMPERATURE (DEGREES KELVIN)	1.75 TO 2.2	.001 TO .0027	0 TO 23
ELEMENTARY PARTICLES OF FLUID	ATOMS	ATOMS	ELECTRONS
MAGNETIC	NO	YES	YES
STATISTICS	BOSON	FERMION	FERMION
ELECTRIC CHARGE	NO	NO	YES
CONDENSED ENTITIES	ATOMS	PAIRS OF ATOMS	PAIRS OF ELECTRONS
SPATIALLY SYMMETRIC	YES	NO	YES
MAGNETIC	NO	YES	NO
EXPEL MAGNETIC FIELD	NO	NO	YES
NUMBER OF SUPERFLUID PHASES	ONE	THREE	ONE

PROPERTIES OF SUPERFLUIDS are determined by the nature of the particles making up the fluid and by the manner in which those particles condense to form the superfluid phase. Superfluid helium 4 is formed through the Bose-Einstein condensation of single helium-4 atoms, which are neutral, nonmagnetic, spinless bosons. In a superconductor the condensed entities are pairs of electrons. The electrons are electrically charged, but the magnetism associated with the electron spin cancels within each pair. Superfluid helium 3 has some features of superfluid helium 4 and some features of a superconductor, but it also has features that are not shared by either of the other two superfluids. Because the pairs are not spatially symmetrical the properties of superfluid helium 3 can show a pronounced dependence on direction; because the pairs are magnetic an entire new category of macroscopically observable quantum behavior has been made available; because the fluid allows the introduction of a magnetic field new magnetic phenomena can be conveniently observed, and because there are three superfluid phases macroscopic quantum behavior is made available for study in a variety of forms.

lium through tiny cracks can be viewed as being analogous to the Ampèrean current in a permanent magnet. In both cases microscopic quantum behavior is amplified to the macroscopic scale. In the case of the magnet the amplification is brought about by the orderly arrangement of the individual atomic currents; in the case of superfluid helium 4 it is produced by the Bose-Einstein condensation of the atoms.

Those who enjoy pondering the mysteries of the quantum theory might pause at this point to contemplate the difference in the behavior of the two helium liquids at temperatures from about .01 degree to two degrees above absolute zero. Liquid helium 3 behaves quite properly; indeed, it gets somewhat sluggish as the temperature drops, becoming as viscous as light machine oil. Liquid helium 4, however, slips through infinitesimal cracks so tiny as to be impenetrable even by a gas, and it otherwise disports itself in unexpected ways. Yet the atoms out of which the two liquids are formed are identical in almost all respects. The only difference is buried deep in the atomic interior. There, well shielded by the almost impenetrable cloud of electrons, in a nucleus that occupies only a billionth of a millionth of the volume of the entire atom, helium 3 lacks a neutron.

Superconductivity

In spite of the early failures to discover a superfluid transition in helium 3, the substance was of considerable interest as a system of fermions that remains in the liquid state even at absolute zero. Although helium 3 is the only conventional liquid to behave this way, analogous systems of fermions are formed by the conduction electrons in metals, by the protons and neutrons in large atomic nuclei and by the neutrons that compose the matter in a neutron star. As a result liquid helium 3 has been of considerable interest to solid-state physicists and of occasional interest to nuclear physicists and astrophysicists. The interplay through the 1950's and 1960's between the study of liquid helium 3 and the study of electrons in metals has been particularly fruitful, in part because helium is in many ways the simpler system. Conduction electrons have a negative electric charge and exist only within a matrix of positively charged metal ions. Helium-3 atoms, on the other hand, are electrically neutral and can be studied in the pure state, contaminated only by a few stray atoms of helium 4.

The possibility that helium 3 might be a superfluid after all arose from this analogy between helium-3 atoms and conduction electrons. We have noted that in many metals the conduction electrons enter a state of electronic superfluidity, or superconductivity, when the metal is cooled to very low tempera-

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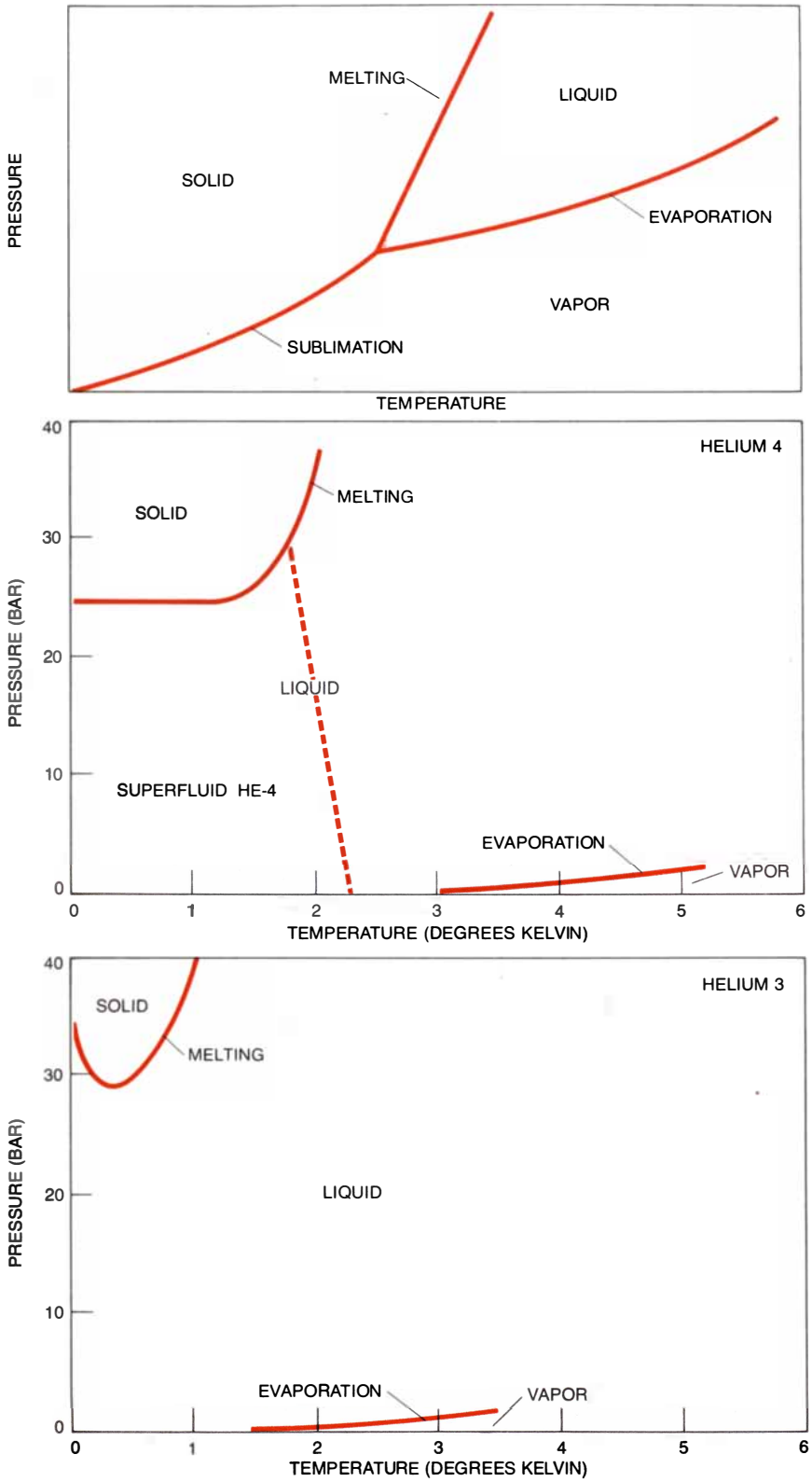

PHASE DIAGRAMS portray the state of a substance at various temperatures and pressures. In most substances (*top*) the liquid phase cannot exist at low temperature, no matter what the pressure is. A familiar example of this behavior is the direct conversion of "dry ice" into gaseous carbon dioxide, with no intermediate liquid phase at sufficiently low temperatures. Helium is unique in remaining a liquid even at absolute zero unless considerable pressure is applied. The boiling point of helium 3 (*bottom*) is about 25 percent lower than that of helium 4 (*middle*), and the freezing pressure is about 25 percent higher. Helium 3 is distinguished by having a point of minimum pressure on its melting curve; at temperatures below that of the minimum the solidification of liquid helium 3 at a fixed pressure requires the application of heat (in contrast to most substances, where heat must be removed). Superfluid phases of helium are not shown here; they are found in a very narrow region at extreme left (*see illustration on page 57*).

tures. In a superconducting metal electric current flows without any discernible loss of energy, much as a superfluid flows without friction through small pores.

Since electrons are fermions, superconductivity cannot be explained by a direct analogy with the superfluid behavior of helium 4; for electrons Bose-Einstein condensation is impossible. A fundamental characterization of the similarities and differences between the superfluidity of electrons and of helium 4 became available in 1956 with the pairing theory of John Bardeen, Leon N. Cooper and J. Robert Schrieffer. Their theory of superconductivity is based on a peculiar feature of the force between conduction electrons in a metal. In a vacuum two electrons repel each other because they carry electrostatic charges of the same polarity. In the interior of a metal, however, the force between electrons may have an attractive component generated through an intermediate interaction of the electrons with the positively charged metal ions.

This attractive force between conduction electrons is quite weak, but at low enough temperatures it can lead to the formation of bound pairs of electrons. Indeed, the pairing theory showed that a system of fermions can form such bound pairs no matter how weak the attractive force; reducing the magnitude of the force merely increases the distance between the electrons making up a pair and lowers the temperature at which the pairs first appear.

The electron pairs produced in this way are all in the same quantum-mechanical state: they are Bose-Einstein condensed. This might appear to contradict the rule that fermions cannot undergo Bose-Einstein condensation. The condensed entities in a superconductor, however, are not single electrons but bound electron pairs. These pairs, being composed of two fermions, are bosons.

Pairing in Helium 3

The Bose-Einstein condensation of pairs of conduction electrons leads to superconductivity for reasons quite similar to those relating the superfluidity of helium 4 to the condensation of its atoms. There are, however, some striking differences between the two kinds of condensation. For one thing, the condensed entities in a superconductor (the electron pairs) can only exist when they *are* condensed, whereas helium-4 atoms exist in both the normal fluid and the superfluid. Furthermore, because the binding force between the electrons is weak the pairs are quite large. Indeed, individual separate pairs cannot exist at all: they overlap one another, the centers of mass of millions of other pairs lying within the interior of any given pair.

The electron-pair theory of super-

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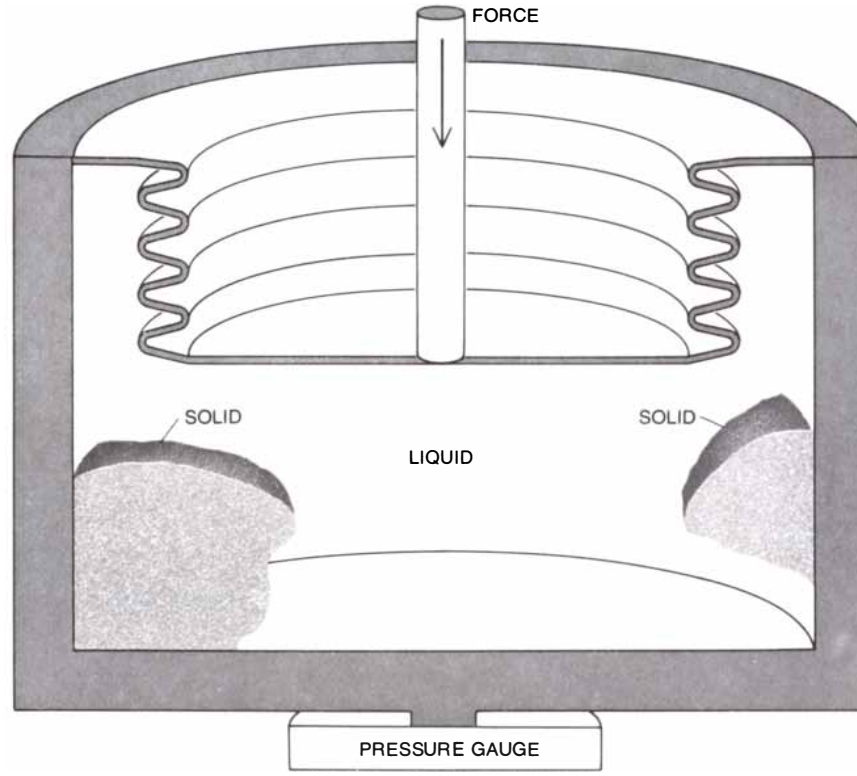
conductivity immediately suggested the possibility of analogous phenomena in helium 3. Like electrons, helium-3 atoms are fermions, and they exert a weak attractive force on one another. This force, the van der Waals force, is common to all neutral atoms, and it is responsible in the first place for the condensation of the gas into the liquid phase. The existence of an attractive force implies that at some low temperature helium-3 atoms should form bound pairs similar to the pairs of electrons in a superconductor and should acquire corresponding superfluid properties.

Although the pairing theory of superconductivity predicted that a superfluid phase of helium 3 should exist, it turned out to be extremely difficult to make reliable calculations of the temperature at which such a superfluid would first appear. Experimental searches for superfluidity in helium 3 were dependent on the development of new methods for achieving lower temperatures. Indeed, some of the most important advances in cryogenic techniques at ultralow temperatures have been by-products of the search itself. As new refrigeration techniques were devised, theoretically predicted transition temperatures were several times found to be too high, and by the mid-1960's, when some of the more pessimistic calculations were indicating that superfluidity would occur only at about a millionth of a degree above absolute zero, the search for superfluidity largely ceased.

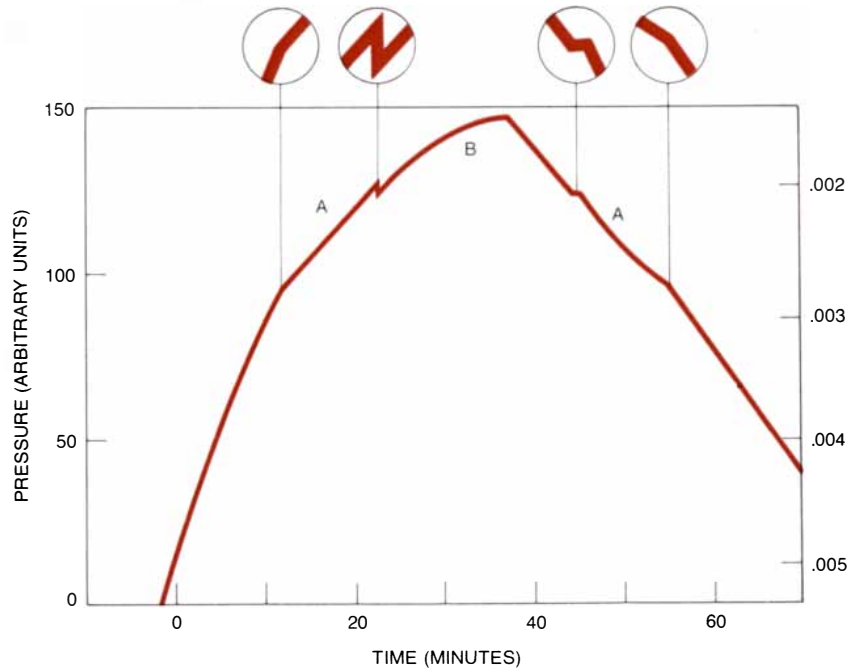
When the transition was finally discovered in 1971, it was found during an investigation (at high pressure) of the magnetic properties of solid helium 3. The discovery was made at Cornell University by Douglas D. Osheroff, Robert C. Richardson and one of us (Lee). Liquid helium 3 was present in the experimental apparatus, but only as a technical ingredient in a refrigeration scheme. This method, known as compressional cooling, is based on the fact that when a mixture of liquid and solid helium 3 is compressed, some of the liquid is converted into a solid and the temperature of the mixture drops. The superfluid transition in helium 3 was first observed at a temperature of .0027 degrees above absolute zero, which is about 1,000 times colder than the superfluid transition temperature of helium 4. It is also, however, 1,000 times higher than the most pessimistic theoretical predictions of the mid-1960's.

In the original Cornell experiment the volume of a cell containing solid and liquid helium 3 was reduced at a constant rate while the pressure inside the cell was continuously measured. The first hint of the superfluid transition was a slight but abrupt change in the rate at which the pressure increased.

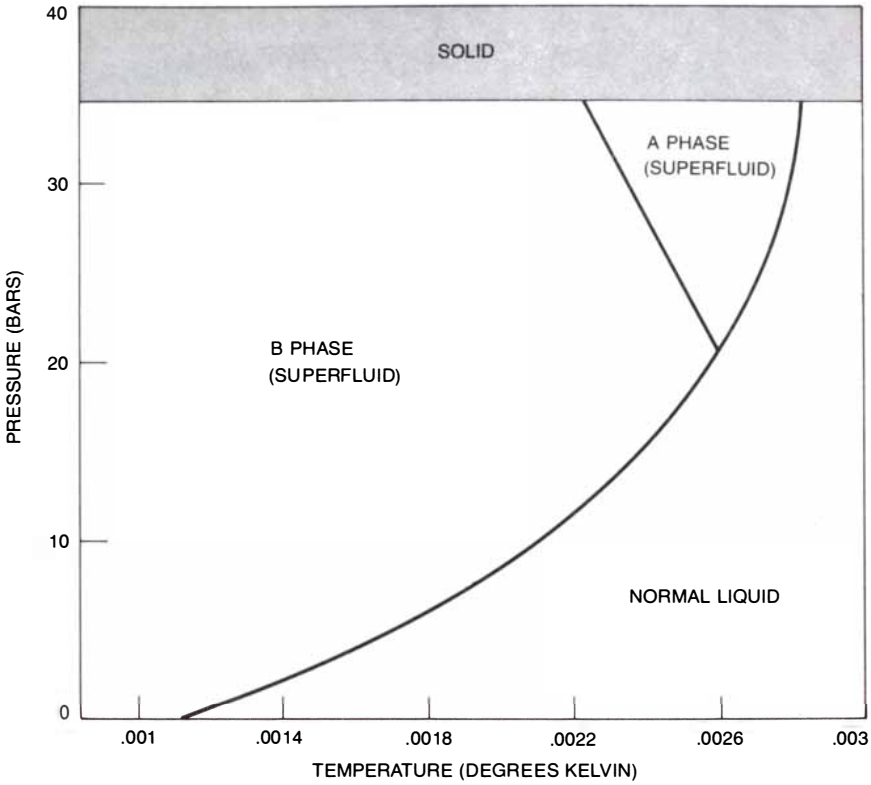
The change in the rate of pressurization of helium 3 was an intriguing anomaly and was originally interpreted as a



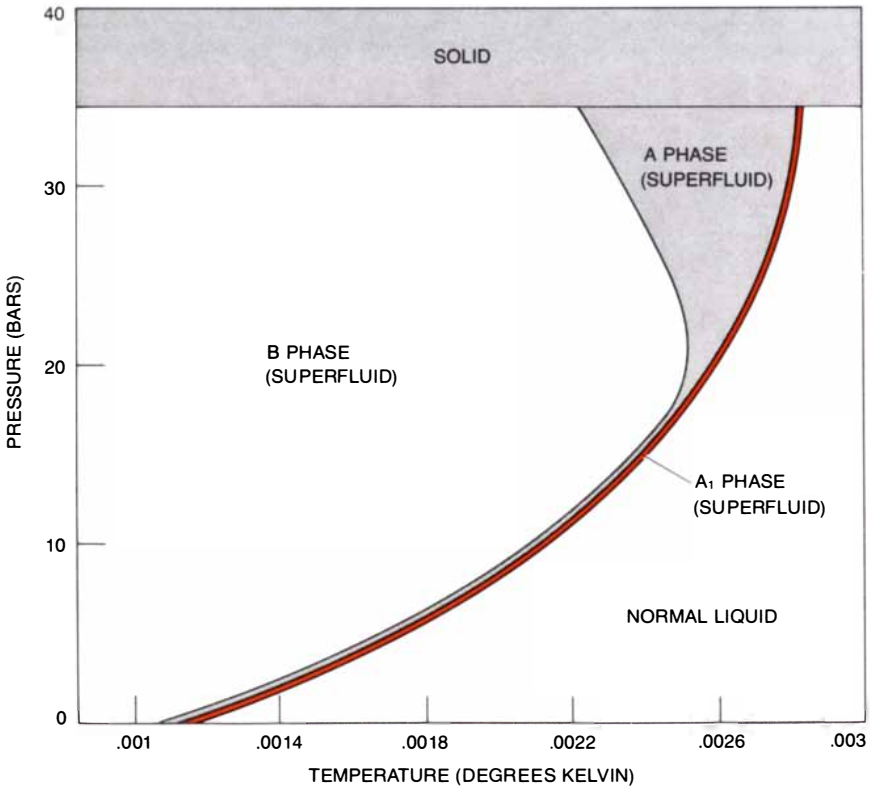
COMPRESSIONAL COOLING achieves extremely low temperatures by exploiting the fact that helium 3 absorbs heat when it freezes. The apparatus is first cooled by an external refrigerator to a temperature of .02 degree Kelvin, well below the minimum point on the melting curve. Then pressure is applied to a chamber containing both liquid and solid helium 3. As the pressure increases, more solid helium crystallizes, absorbing heat from the liquid and further cooling both phases. The superfluid phases of helium 3 were discovered in an experiment employing this method of refrigeration. Anomalous pressure behavior that signaled superfluid transition in the liquid was monitored with a sensitive pressure gauge at bottom of chamber.



FIRST EVIDENCE OF TRANSITIONS to superfluid phases in helium 3 appeared as small changes in the rate of cooling and warming in a compressional cooling cell like the one illustrated at the top of the page. The graph records the pressure in the cell (*scale at left*) as its volume was first reduced at a uniform rate, then expanded. From the pressures it is possible to calculate the equivalent temperatures (*scale at right*). Small discontinuities represent transitions from normal liquid to *A* phase to *B* phase, then a return through *A* phase to normal liquid.



DETAILED PHASE DIAGRAM of helium 3 (the plane of zero magnetic field in the illustration on page 57) displays existence of superfluids close to absolute zero. In absence of magnetic field there are just two superfluid phases, *A* and *B*, which differ in magnetic and mechanical properties. In absence of external magnetic field *A* phase exists only at elevated pressure.



MAGNETIC FIELD alters the helium-3 phase diagram. In an external field the *A* transition is split into two transitions by the appearance of a new superfluid phase, A_1. In a magnetic field both *A* and A_1 phases may extend within a narrow region of diagram all the way to zero pressure, and it is not possible to go directly from the normal liquid to the *B* phase of the superfluid. These phase-transition lines correspond to the intersections in the illustration on page 57 of a plane parallel to the P-T plane with the surfaces that separate the superfluid phases.

clue that a predicted magnetic transition was taking place within the solid helium 3 in the cell. Additional information about the effect was sought by a standard technique for investigating magnetic phenomena: nuclear-magnetic-resonance spectroscopy. The basis of this procedure is that a suitably applied external magnetic field can exert a twisting force on the orientation of a magnetic atomic nucleus, just as magnetic forces can turn a compass needle. Since all magnetic nuclei also spin like gyroscopes, however, they respond to such twisting forces with the complicated precessional motion characteristic of a spinning top. If the applied field has the right frequency, the induced motion can result in the emission of a radio-frequency signal, from which various features of the nuclear magnetism and spin can be inferred.

Liquid of Fermion Pairs

These magnetic-resonance measurements revealed that the pressure anomaly is accompanied by a striking change in magnetic properties: below the temperature of the anomaly there developed an enormous shift in the frequency of the signal broadcast by the helium-3 nuclei. This shift was far too large to be explained by any conventional theories of resonance spectroscopy. Furthermore, the shift was found to be taking place not in the characteristic signal emitted by the helium-3 atoms in the solid phase: it was unambiguously associated with the signal coming from the liquid.

The discovery of strange behavior in liquid helium 3, whatever the details, was widely regarded as evidence of the long-sought superfluid phase. A little more than a year after the discovery Anthony J. Leggett of the University of Sussex constructed a theory that accounted for the observed magnetic anomalies and predicted a number of new magnetic phenomena, many of which have since been observed. Leggett's work combined the theory of nuclear magnetic resonance with the theory describing the pairing of particles in an electrically neutral liquid of fermions. Its success convinced almost everyone (except, for a time, Leggett himself) that the new states of liquid helium 3 were indeed superfluids based on the pairing of helium-3 atoms.

The later discovery of more traditional nonmagnetic manifestations of superfluidity came almost as an anticlimax. The first indications of unusual flow properties were detected in 1973 in the laboratory of Olli V. Lounasmaa at the Helsinki University of Technology. More direct evidence of superfluid properties was obtained the following year in the laboratory of John C. Wheatley at the University of California at San Diego and in the laboratory of John D.

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The famous sound of Morse code's dah-dit may be phasing out for the maritime industry. This is because two communications satellites are in synchronous orbit over the Atlantic and Pacific oceans. These maritime satellites, built by Hughes, are owned and operated by a consortium of carriers headed by COMSAT General Corporation. Called Marisat, the satellites are currently relaying high-quality voice, telex, facsimile, and data over both oceans for the international maritime industry. Marisat also serves the US Navy for fleet communications.

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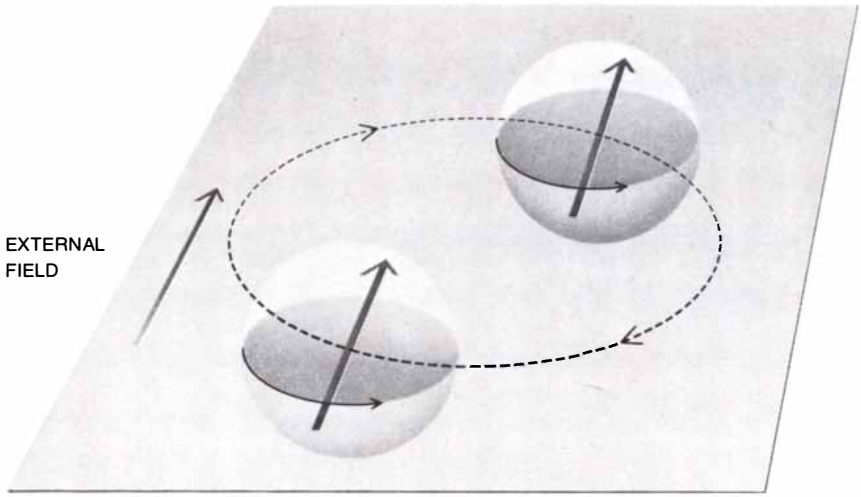

PAIR STRUCTURE in the A_1 phase of helium 3 is the simplest to describe of the pair structures in the three superfluid phases of the isotope. The elementary nuclear magnets associated with the pair of atoms are oriented so that the net magnetism of the pair lies along the direction of magnetic field. Members of pair rotate around each other in a plane containing the field.

Reppy at Cornell. In these experiments a chamber was so tightly packed with material that the interstitial spaces were exceedingly small. Liquid helium 3, forced into the tiny interstices in the chamber, was found to be completely immobilized above the transition temperature. Below the transition temperature, however, unmistakable evidence was observed that liquid was sloshing freely through the chamber. Only after the publication of these experiments in 1974 was the discovery sanctified by the appearance of a new index category: "Superfluid helium 3." By then, however, no one was surprised.

The Most Super Superfluid

From the time superfluid helium 3 was discovered it has been apparent that it is an even stranger substance than superfluid helium 4 or superconductors. The very first experiments revealed not one superfluid transition but two. They took place at .0027 and .0021 degrees K. when the pressure was 34 atmospheres. The two new phases that appear as the liquid is cooled through these temperatures have been named ^{3}He-A and ^{3}He-B. When the cooling is done in a magnetic field, still another phase, ^{3}He-A_1, appears in a narrow range of temperatures between the A phase and the normal liquid. Thus in a small region of the phase diagram helium 3 exists in five distinct phases: the solid, the normal liquid and three kinds of superfluid. The multiplicity of distinct superfluid phases in helium 3 and several other properties of the liquid set it apart not only from ordinary liquids but also from helium 4 and superconductors.

When helium 4 is compared with what we now know about superfluid helium 3, it appears to be a rather humdrum superfluid. Since helium-4 atoms have no spin and no magnetism, the superfluid they form is magnetically inert. Furthermore, the spatial structure of the helium-4 atom is the least interesting possible: it is a perfect sphere, devoid of any distinguishing features and hence incapable of favoring one direction or orientation over any other. Because of its high degree of internal symmetry the helium-4 atom is rather like the fictitious point particle of the textbooks. Except under conditions so extreme as to squash it out of its symmetrical shape, nothing can be said about a helium-4 atom other than where it is or how fast it is going. This absence of internal structure in the atom limits the kinds of phenomena that can take place in the superfluid phase; the only quantum-mechanical behavior revealed on a macroscopic scale in superfluid helium 4 is that relating to the motion of matter from place to place.

In principle a superconductor might be a more interesting superfluid, since electrons do have spin and the accompanying magnetism. In all known superconductors, however, the two electrons in a pair are oriented with their magnetic poles pointing in opposite directions. As a result the magnetic fields of the electrons cancel and the pairs are as inert magnetically as helium-4 atoms. Furthermore, like helium-4 atoms, the electron pairs in all known superconductors are as devoid of structure as the spherical electron cloud surrounding a helium atom.

Helium 3 is the only superfluid in which the condensed objects have an internal structure. One underlying reason for this structure is that in helium 3 the nuclear magnetic poles of the two atoms forming a pair are aligned in the same direction. Rather than canceling each other the magnetic fields reinforce, so that the pairs are themselves magnetic.

That helium-3 nuclei might pair in this way was anticipated more than a decade before the superfluid phases were discovered, although it was impossible to predict with assurance whether the atoms would prefer the magnetic configuration or the nonmagnetic one. That the pairing is in the more interesting magnetic form was established by nuclear-magnetic-resonance measurements made soon after the discovery. The magnetic-resonance effects could be elegantly accounted for in terms of the precession of axes characterizing the magnetic orientation of the pair. In addition the existence of more than a single superfluid phase followed from general quantum laws specifying the distinct possible configurations (or quantum states) available to an object made up of two fermions with similarly directed magnetic poles.

The net magnetism of the pairs in helium 3 has further consequences. Since the nuclear magnets of both members of the pair are similarly directed, the pairs in superfluid helium 3 cannot have the symmetry characteristic of electron pairs in a superconductor. If the two atoms were distributed about the center of mass with perfect spherical symmetry, then they would be the same in all respects, in violation of the rule that two fermions cannot occupy precisely the same state. (The electrons forming the nonmagnetic pairs in a superconductor are allowed to move around each other

FRICTIONLESS FLOW OF HELIUM 3 provides convincing evidence that the new phases of the liquid are in fact superfluids. Powder is packed tightly into a tube, making it nearly impervious to fluid flow above the superfluid transition. In the superfluid phase, however, some of the liquid flows freely through the powder. In practice the experiment is performed with an oscillating current of superfluid, which thus moves back and forth through the powder.

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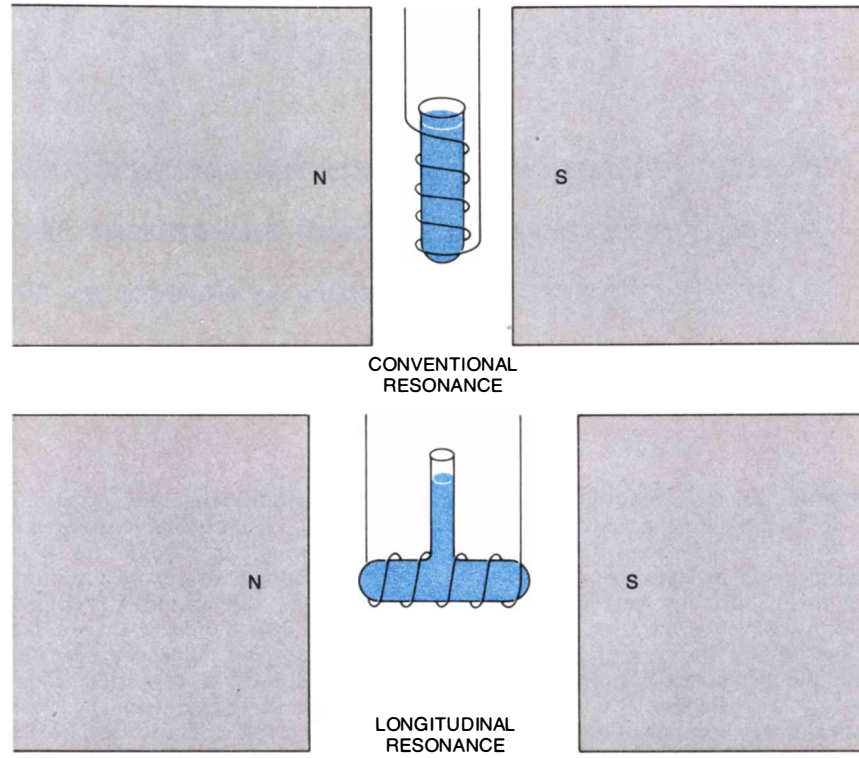
with perfect spherical symmetry because their internal magnets are oppositely directed, thereby meeting the requirement that two fermions not be alike in all respects.)

The different superfluid phases of helium 3 can be given detailed characterization in terms of this internal structure of the condensed pairs. The simplest of the phases is the A_1 phase, which exists only in a narrow range of temperatures just below the transition temperature when the fluid is exposed to a magnetic field. The nuclear spins and magnetic axes of all the pairs in the A_1 phase are aligned with each other and with the external field. (It is not yet known, however, whether they are along the field or opposed to it.) Furthermore, the two members of every pair rotate around each other in a single plane parallel to the applied field.

The A and B phases, which do not require an external field to stabilize them, involve more complicated kinds of motion. Both the magnetic axis of the pair and the axis associated with its asymmetrical shape can be oriented in three possible ways, determined by well-established quantum laws. The A and B phases are characterized by various combinations, or "superpositions," of these configurations, whose quantum-mechanical descriptions defy simple translation into classical language.



NUCLEAR MAGNETIC RESONANCE is usually carried out by studying the response of a system to a magnetic signal from a radio-frequency coil whose axis is perpendicular to an applied steady magnetic field. When helium 3 is studied by this technique, it reveals a frequency shift that is far too large to be explained by theories of conventional resonance in normal systems. The types of pairing believed to characterize the A and B superfluids, however, can produce a shift of the observed size. Pairing theories also predict that the nuclear-magnetic-resonance signals can be observed with coil oriented not perpendicular to applied steady field but parallel to it. This unusual type of signal has now been observed in both A and B phases.

Other Properties

Because of the internal structure of the pairs superfluid helium 3 has many striking properties that cannot be observed in the other superfluids. One example is the anisotropy of superfluid helium 3. Since all the pairs of atoms in the superfluid are in the same state, their asymmetrical shape is expressed in properties of the fluid as a whole. If a direction is defined by the imposition of a magnetic field, many properties of the fluid are found to depend on direction with respect to the field. For example, the rate of attenuation of sound in the liquid and the rate of superfluid flow depend on whether they are measured parallel to such a field or perpendicular to it. The dependence of mechanical properties on the direction of an applied magnetic field is commonly observed in many solids. Similar anisotropies are also observed in the esoteric liquids known as liquid crystals. What makes superfluid helium 3 unique is that in all other cases the external field interacts directly with the electrons of the atoms making up the medium. These electrons in turn are directly responsible for the mechanical properties affected by the field. In helium 3, however, the magnetic field interacts only with the tiny nuclear magnets buried deep in the interior of the atoms. That altering the direction of the nuclear magnets could have an effect on anything as gross as the attenuation of sound was unheard of before the discovery of superfluid helium 3. This is a direct manifestation of the delicate correlations, within each pair, of the two axes describing the magnetism and the spatial asymmetry.

The most intensively studied of the macroscopic quantum effects of helium 3 are those directly associated with nuclear magnetism. The signals emitted on magnetic stimulation of the superfluid phases bear little relation to patterns recorded with any other substance. We have already mentioned the anomalously large shift in the magnetic-resonance signal, observed in the earliest experiments. Each of the three phases has its own characteristic pattern of shifts, some of them (called longitudinal resonances) arising in configurations in which the conventional resonance theory predicts no signal at all. Perhaps the most impressive of these longitudinal effects arises when the strength of a static applied magnetic field is suddenly changed. When this is done in ordinary materials, the induced magnetization of the entire material somewhat sluggishly follows along, slowly subsiding to the new value appropriate to the new field strength. In superfluid helium 3 the magnetism responds to such a change in a lively oscillatory manner.

Another prediction, which is yet to be tested, is that the most stable configuration of the A phase in a stationary container should be one in which the liquid forever rotates. Superconductors and superfluid helium 4 have similar states, but they are never the most stable ones, and they can in principle decay into nonrotating configurations.

These examples are only fragments of the growing list of observed and predicted properties of the new superfluid phases of helium 3. These new superfluids have generated intense interest among physicists, in part because of the opportunities they afford to see quantum mechanics at work, as it were, in a bottle. By presenting modes of superfluid behavior substantially more general than anything available in helium 4 or superconductors, they are also forcing low-temperature physicists to reexamine and extend the theories evolved over a 50-year span to account for the behavior of pre-1971 superfluids. This kind of process can be physics at its best. At the very least it will lead to a deeper understanding of the general phenomena of superfluidity and superconductivity. And the hope has even been voiced that the effort to explain the nature of superfluid helium 3 could lead to further insight into the well-established but still profoundly mysterious structure of the quantum theory itself.

The Control of Walking

Recent experiments indicate that the mechanism by which the nervous system generates the rhythmic movements of the leg during walking is basically the same in animals as diverse as the cat and the cockroach

by Keir Pearson

The scientific analysis of walking began a little more than 100 years ago as the result of a dispute, lingering from ancient times, about whether or not all four feet of a galloping horse are ever off the ground at the same time. In an effort to resolve the matter the pioneer action photographer Eadweard Muybridge in 1872 set up an electrically triggered series of cameras and succeeded in obtaining a fast sequence of photographs of a galloping horse at a racetrack in California. Reproductions of the photographs showing all four of the horse's feet off the ground appeared in many publications, including the October 19, 1878, issue of *Scientific American*. The clarity of these early pictures soon led Muybridge to realize that his photographic technique could be extended to analyze the walking movements of all kinds of animals in unprecedented detail. He subsequently photographed a host of walking and running animals, including cats, dogs, monkeys, camels, elephants, raccoons, pigs, kangaroos and birds. His remarkable collection of photographs was finally published in 1887 in a monumental 11-volume work titled *Animal Locomotion*.

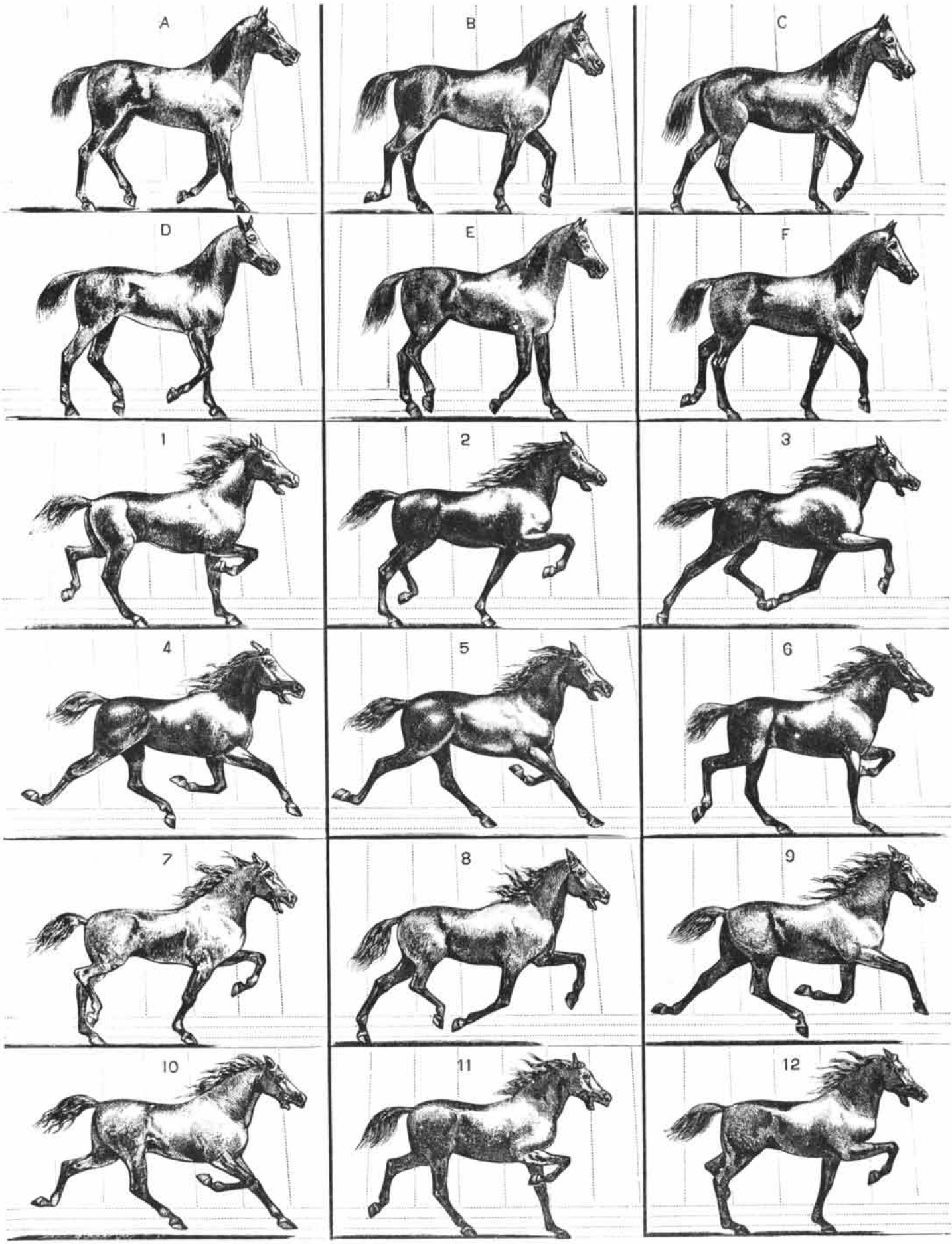
How does an animal's nervous system generate the rhythmic walking movements of the leg that were so amply documented by Muybridge? The effort to answer the question began early in this century with the work of two British physiologists, C. S. Sherrington and T. Graham Brown. Sherrington first showed that rhythmic movements could be elicited from the hind legs of cats and dogs some weeks after their spinal cord had been severed. Since the operation had isolated from the rest of the nervous system the nervous centers that control the movement of the hind legs, it followed that the higher levels of the nervous system are not necessary for the organization of stepping movements.

Another notable discovery of this period, although it was not generally recognized as such until quite recently, was Graham Brown's demonstration in 1911 that rhythmic contractions of leg muscles, similar to those that occur during walking, could be induced immediately following transection of the spinal cord even in animals in which all input from sensory nerves in the legs had been eliminated. This discovery led Graham Brown to propose that mechanisms located entirely within the spinal cord are responsible for generating the basic rhythm for stepping in each leg. Earlier Sherrington had stressed the importance of sensory input from peripheral nerve receptors in initiating and coordinating such movements; he explained the generation of rhythmic leg movements by a series of "chain reflexes" (a reflex being a stereotyped movement elicited by the stimulation of a specific group of sensory receptors). Thus he conceived that the sensory input generated during any part of the step cycle elicits the next part of the cycle by a reflex action, producing in turn another sensory signal that elicits the next part of the cycle, and so on.

The two concepts of a spinal rhythm-generator for each leg and a triggering of leg movements by sensory signals are not incompatible. Indeed, Graham Brown considered that reflexes reinforced the centrally generated rhythm, a view that Sherrington later came to share. In 1924 Sherrington wrote: "From the observations of Professor Graham Brown, an intrinsic activity in spinal centres seems the essential nervous mechanism responsible for inconscient stepping, a central activity comparable with that of the respiratory centre in the bulb [the brain stem], and like the latter, highly regulable by reflex action." Recent experiments in a number of laboratories have yielded results that strongly support this dual view of the nervous mechanisms involved in walking.

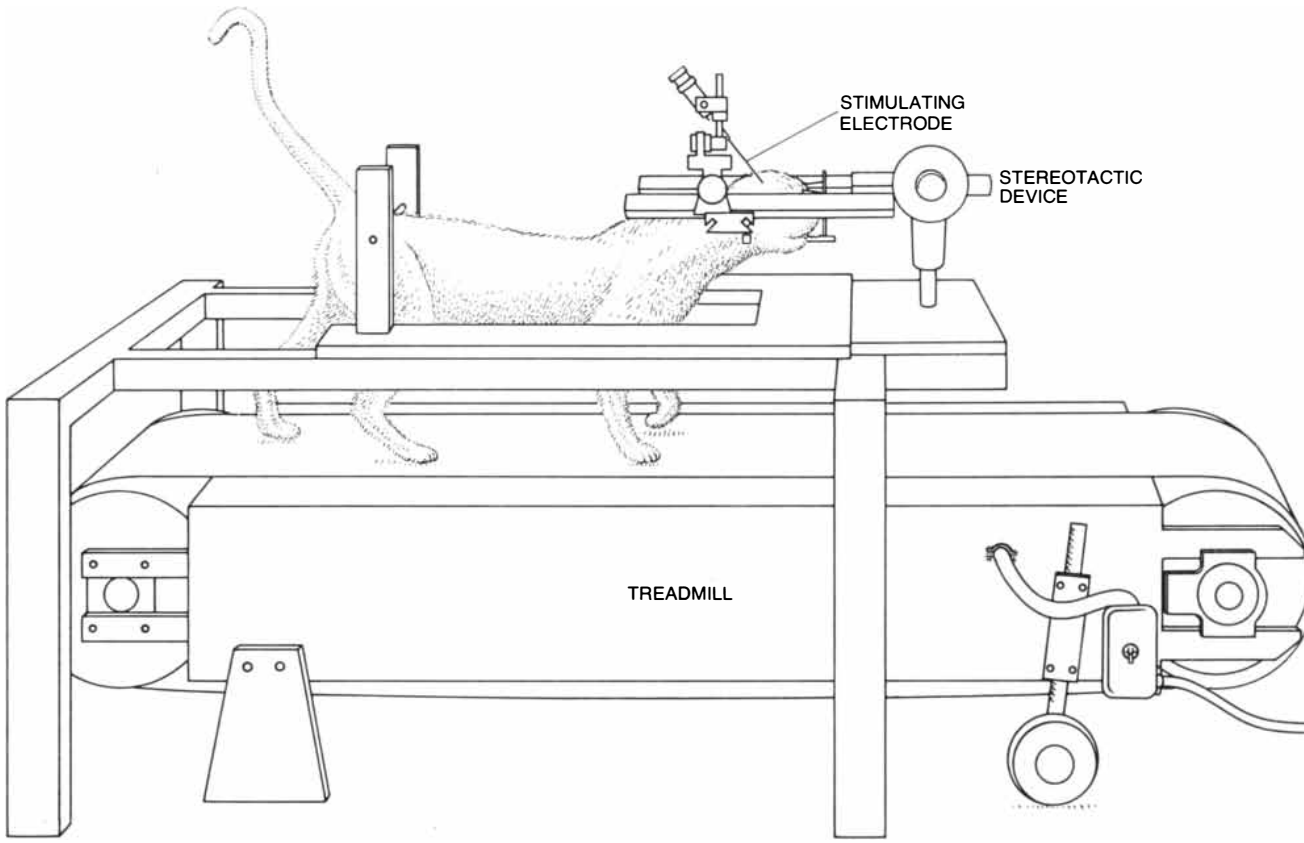
For almost 40 years following the investigations of Sherrington and Graham Brown there were no significant advances in our understanding of how the nervous system controls walking. The major emphasis of research in this interlude was to determine the organization and the properties of the spinal reflexes. In general little effort was made to relate these findings to the normal behavior of the animal. Contemporary research on the nervous control of walking began in the 1960's with the recording of the patterns of muscle activity in a

EARLY STUDY of the walking and running movements of the horse is represented by the engraving on the opposite page, made from two rapid sequences of photographs obtained by the 19th-century photographer Eadweard Muybridge with the aid of an electrically triggered series of cameras; the illustration is reproduced from the opening page of the October 19, 1878, issue of SCIENTIFIC AMERICAN. The article accompanying the illustration, titled "A Horse's Motion Scientifically Determined," points out that the two series of "instantaneous photographs," forwarded by Muybridge following the appearance in the magazine of a short note about his experiments in California, show "the movement of the horse 'Abe Edgington,' [the first] while walking...; the second showing the same horse while trotting.... The exposure for each negative was about the two thousandth part of a second. The vertical lines on the background are twenty-eight inches apart; the heavy horizontal line represents the level of the track; the others mark elevations of four, eight, and twelve inches respectively.... It will be seen that the walking horse always has two feet on the ground, and, for a brief interval in each stride, three feet. The positions of the feet shown in Figs. A and E indicate a stride of four feet four inches. When trotting... the stride of the same horse is over 18 feet. Figs. 1 to 12 show the latter motion. In Figs. 4 and 5, and again in 9 and 10, the horse is entirely off the ground, literally flying through the air.... The most careless observer of these figures will not fail to notice that the conventional figure of a trotting horse in motion does not appear in any of them, nor anything like it. Before these pictures were taken no artist would have dared to draw a horse as a horse really is when in motion, even if it had been possible for the unaided eye to detect his real attitude.... Mr. Muybridge's ingenious and successful efforts to catch and fix the fleeting attitudes of moving animals thus not only make a notable addition to our stock of positive knowledge, but must also effect a radical change in the art of depicting horses in motion."

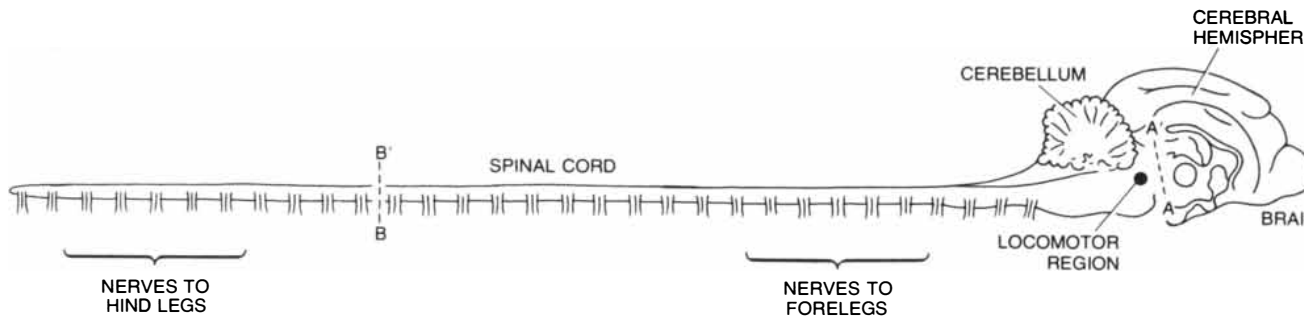


freely walking cat by Ingmar Engberg and Anders Lundberg in Sweden.

Then in 1965 the exciting discovery was made by the Russian workers M. L. Shik, F. V. Severin and G. N. Orlovskii that cats lacking the higher levels of the nervous system (the cerebral hemispheres and the upper brain stem) could be made to walk in a controlled manner on a treadmill. After the cat's upper brain stem is cut and the forebrain is removed electrical stimulation of the locomotor region in the remaining brain stem can cause the animal to walk when it is placed on a treadmill. The stepping movements on the treadmill are similar in all respects to those observed during normal walking; the gait the animal adopts depends on the speed of the treadmill and the strength of the stimulating current. With a low treadmill speed and a weak stimulus the animal will walk. Increasing the speed of the treadmill and the strength of the stimu-



EXPERIMENTAL ARRANGEMENT employed in the author's laboratory at the University of Alberta to study the nervous control of walking in the cat was adapted from a method developed about a decade ago by a team of investigators in the U.S.S.R. The animal is first anesthetized and the higher regions of the nervous system are removed after severing the brain stem (*see illustration below*). Following this operation the animal is in a vegetative state, the only movements being those associated with respiration. By electrically stimulating the locomotor region of the remaining brain stem, however, the cat can be made to walk in a normal manner when placed on a treadmill. The rate of walking can be completely controlled by the experimenter by varying the speed of the treadmill and the strength of the stimulation. Because the animal is walking at a fixed position in space this arrangement, now used in a number of laboratories, makes it possible to record the electrical activity of the nerve cells within the spinal cord, the brain stem and the cerebellum.



SPINAL CORD AND LOWER BRAIN STEM are isolated from the cerebral hemispheres and upper brain stem of the cat by cutting the brain stem at the line marked *A–A′* in this cross-sectional diagram of the cat's central nervous system. In an alternative experimental approach, developed early in this century by C. S. Sherrington, the hind-leg segments of the spinal cord are isolated by cutting the cord at the line marked *B–B′* in the diagram. In the latter case the hind legs will walk on a treadmill immediately after the operation if the animal is treated with certain drugs. Without drug treatment recovery period of a few weeks is required before hind legs will walk.

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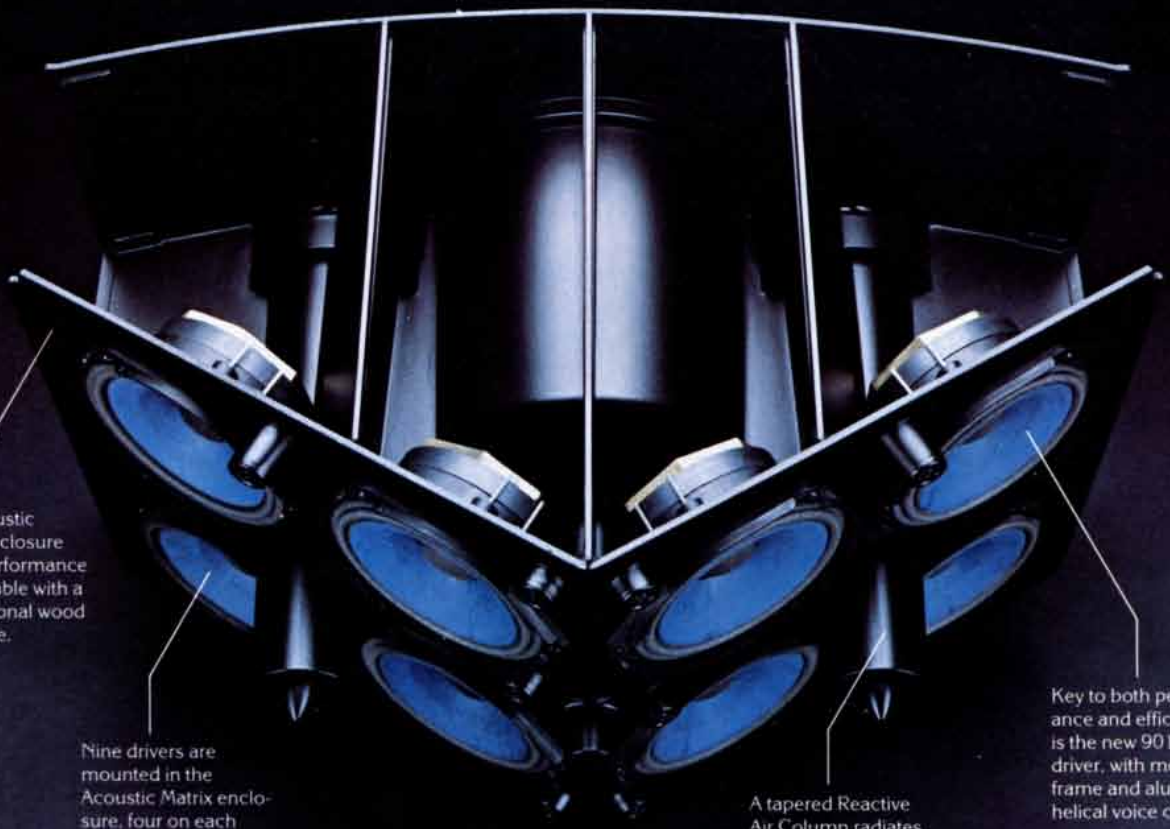

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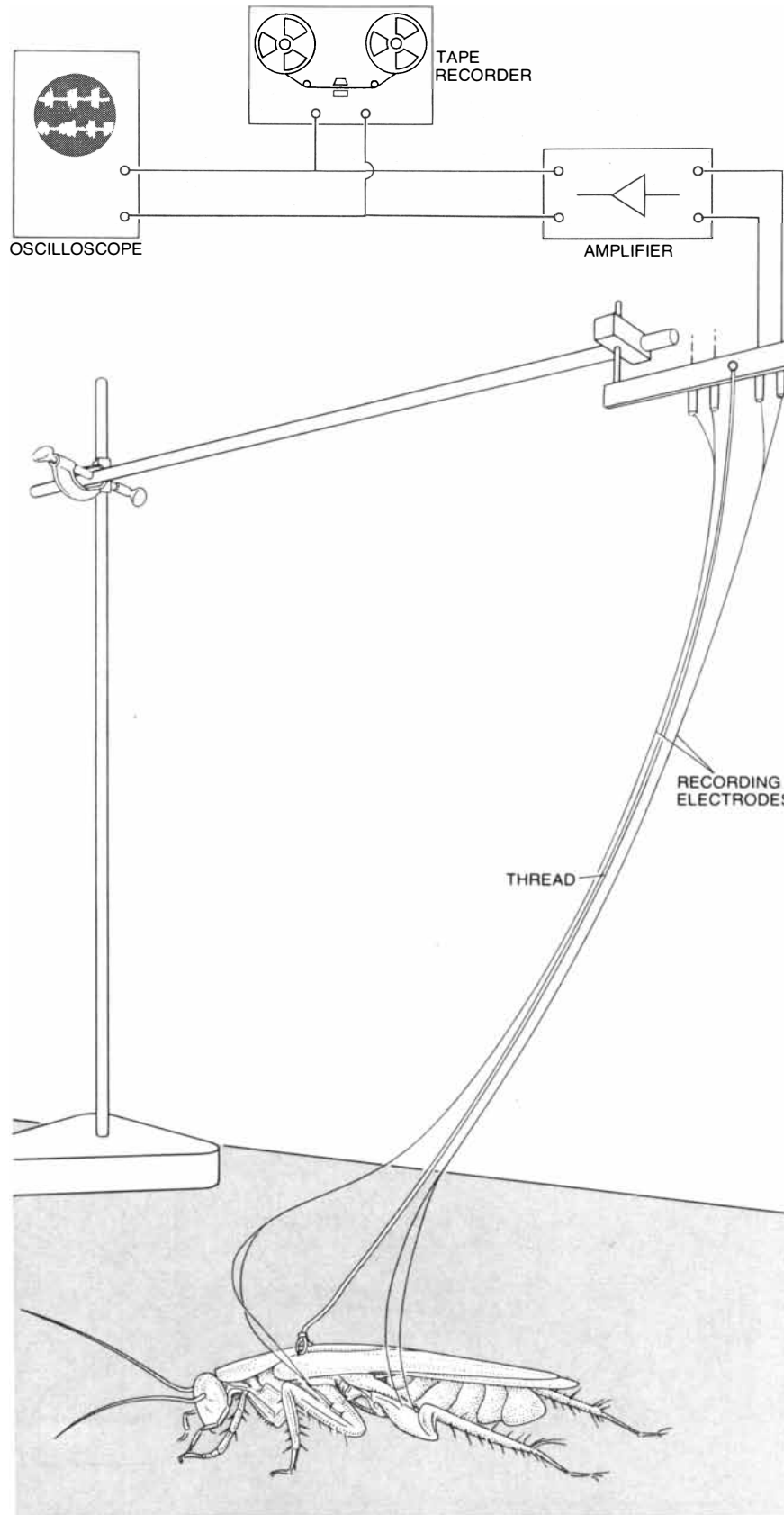
lus will cause the animal to trot, and with higher treadmill speeds and stronger stimuli the animal will gallop. Hence the walking behavior of the animal can be completely controlled by the experimenter. The great advantage of this experimental arrangement is that it enables one to make electrical recordings from nerve cells within the nervous system while the animal is walking, since the animal is fixed at one position in space.

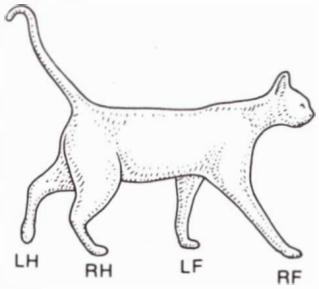
Throughout this century there have also been numerous studies of the nervous control of walking in amphibians (such as toads and newts) and arthropods (insects, crabs and crayfish). Much of the early work on these animals was done at a time when the dominant concept in neurophysiology, originating with the work of Sherrington and I. P. Pavlov, was that reflexes were the basic units of behavior. Hence it is not surprising that the early hypotheses on the control of walking in amphibians and insects held that reflexes were essential for the generation of the stepping rhythm. Quite recently, however, substantial evidence has accumulated demonstrating that this notion is incorrect and that the basic rhythm is generated within the central nervous system and is modified by sensory input. One consequence of this demonstration is the realization that the basic stepping mechanism of the cockroach, say, is similar to that of the cat. Indeed, the relative simplicity of the walking system of the cockroach has provided much information on the mechanisms by which reflex activity modulates the centrally generated rhythm, which in turn has led to concepts that may make it possible to gain an understanding of the more complex systems.

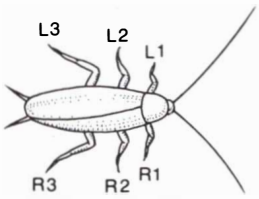
Most current research on walking has been directed toward four goals: (1) gaining a precise description of leg movements and determining which muscles produce these movements, (2) establishing that mechanisms within the central nervous system generate the basic rhythm for stepping, (3) determining the function of the sensory input from leg receptors and (4) determining the nervous mechanisms for coordinating stepping in different legs. The two animals most intensively studied have been the cat and the cockroach. Here I shall summarize some of the main findings from experiments involving the two animals, emphasizing those similarities that suggest general principles about the control of walking.

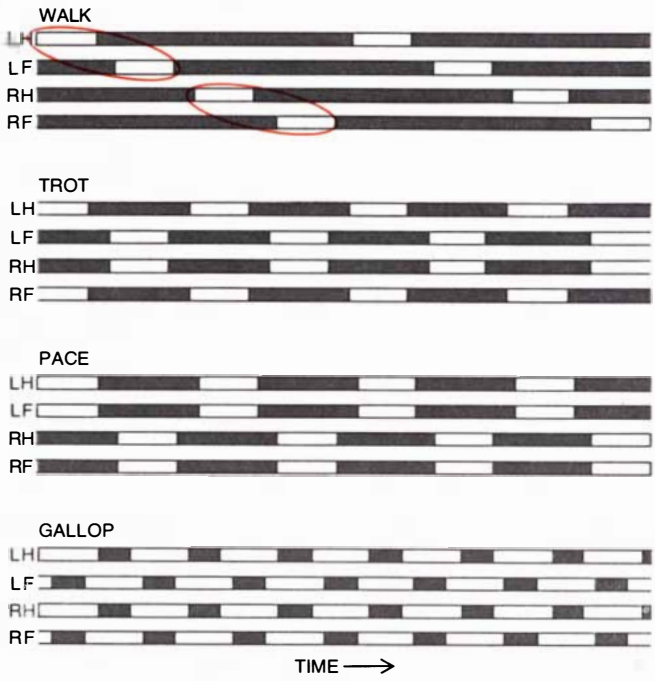
In the cat there are four basic gaits: the walk, the trot, the pace and the gallop [*see top illustration on next page*]. During walking, trotting and pacing the stepping movements of the two hind legs alternate with each other, as the stepping movements of the two forelegs do.

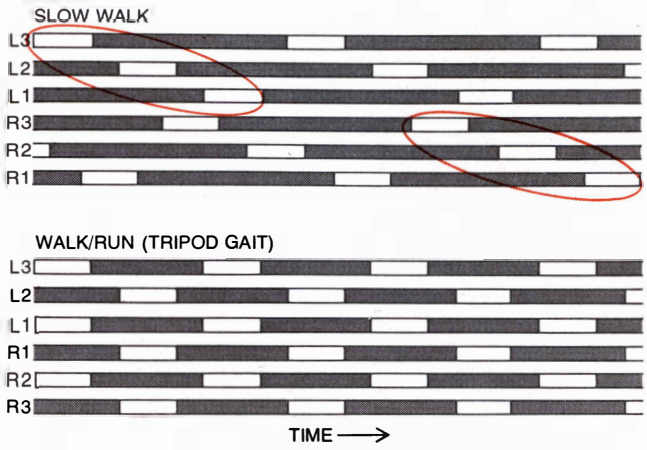


ELECTRICAL ACTIVITY in the leg muscles of a freely walking cockroach is recorded by means of the apparatus shown here, devised by the author and his colleagues. Fine recording wires are implanted in the flexor and extensor muscles of the insect's leg and are anchored to the leg by tying them to the cuticle (the hard outer skeleton). The recording leads and a restraining thread are attached to a fixed terminal above the cockroach, and their length is adjusted so that the animal can walk about freely in a test area some two feet in diameter.

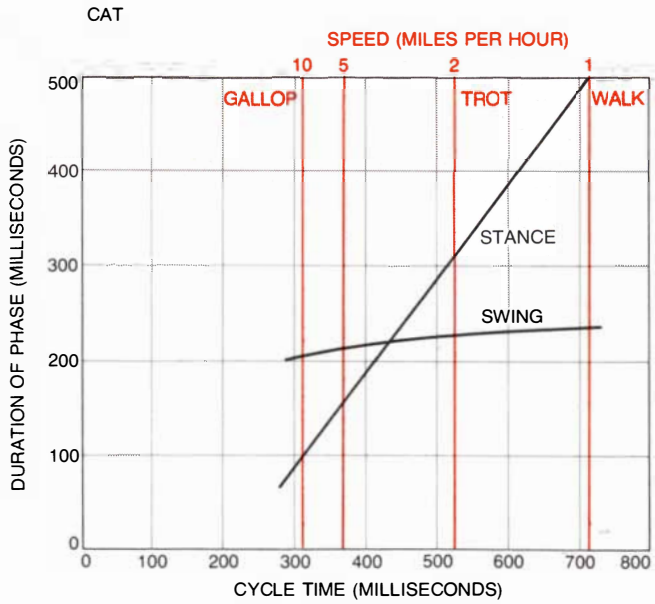


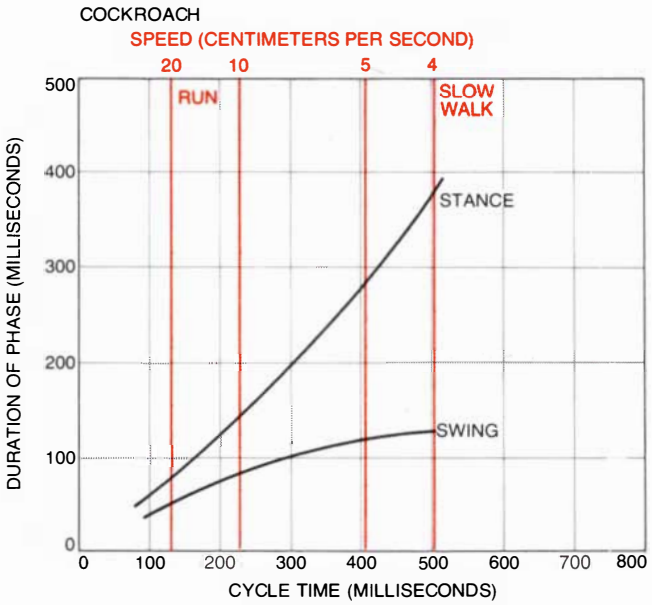






STEPPING PATTERNS of the cat and the cockroach are depicted schematically in these diagrams. Reading from left to right, each horizontal bar indicates for a single leg the time the foot is off the ground (*white parts of bar*) and on the ground (*gray parts of bar*). During slow walking there is a back-to-front sequence of stepping for both animals; the sequences are marked by the colored ellipses.





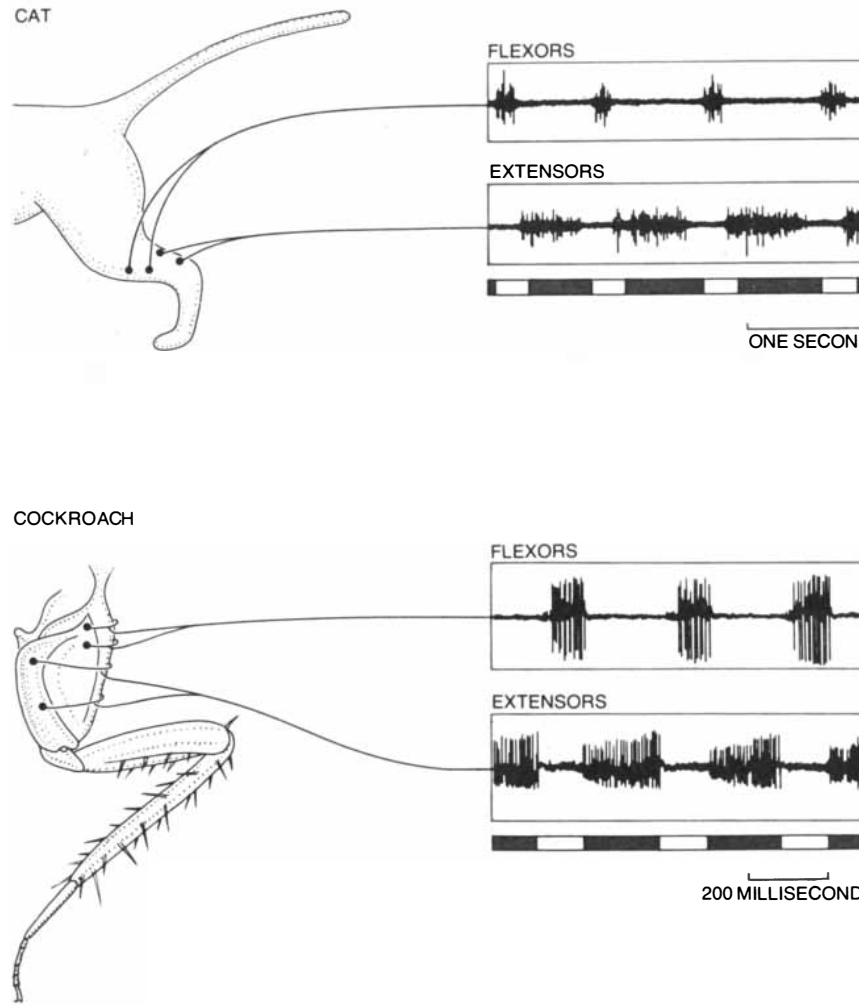
DURING NORMAL WALKING the duration of the swing phase of a step (when the foot is off the ground) remains fairly constant compared with changes in the duration of the stance phase (when the foot is on the ground) for most animals. These two graphs show the durations of the swing phase and the stance phase for the hind legs of the cat and the cockroach in relation to cycle time: the interval from the beginning of one swing phase to the beginning of the next. Colored scales indicate speed, measured in appropriate units for each animal.

The differences between the three gaits lie in the timing of the stepping of the two legs on one side of the animal. During slow walking the left foreleg, for example, steps shortly after the left hind leg and before the right hind leg. Hence the stepping sequence is left hind leg, left foreleg, right hind leg, right foreleg, and so on.

The transition from walking to trotting is continuous, since with an increase in walking speed a foreleg begins to step before the opposite hind leg touches the ground. When the speed is such that diagonally opposite legs step at the same time, the animal is trotting. Pacing, which is done at the same speed as trotting or at a slightly higher speed, is characterized by the simultaneous stepping of the two legs on one side. During galloping opposite legs move almost synchronously and the forelegs alternate with the hind legs. The general feature that emerges from this analysis is that the coupling between adjacent legs (along and across the animal) is either in phase (stepping together) or out of phase (alternating).

The gaits commonly seen in amphibians and arthropods resemble the walking and trotting gaits of cats. In the cockroach, which of course has six legs, the stepping of adjacent legs alternates during moderate-speed and high-speed walking. Thus the stepping of the three legs right rear, left middle and right front alternates with the stepping of left rear, right middle and left front. The animal is therefore always supported by at least three legs, and for that reason the gait is referred to as the tripod gait. As the walking speed decreases, the gait is best described as a back-to-front sequence for the three legs on each side of the animal. At all times the two legs on any one segment of the insect strictly alternate.

For slow walking a feature common to the cat and the cockroach is the back-to-front sequence of stepping. The same is true of most other animals, a fact that is seen clearly in many-legged animals such as millipedes and centipedes, where "waves" of stepping appear to move from back to front.



RECIPROCAL BURSTS of electrical activity are recorded in the flexor muscles and the extensor muscles during the swing phase (*white*) and the stance phase (*gray*) respectively, both for the cat walking on the treadmill (*top*) and for the cockroach walking about freely (*bottom*). The period of electrical activity corresponds to the time during which muscle is contracting.

The step cycle for an individual leg consists of two basic phases: the swing phase, when the foot is off the ground and moving forward, and the stance phase, when the foot is on the ground and the leg is moving backward with respect to the body. The propulsive force for progression is developed during the stance phase. A common feature of the step cycle in the cockroach and the cat (and in most other animals, including man) is that the duration of the swing phase remains comparatively constant as walking speed varies. Accordingly changes in the speed of progression are produced primarily by changes in the time it takes for the legs to be retracted during the stance phase.

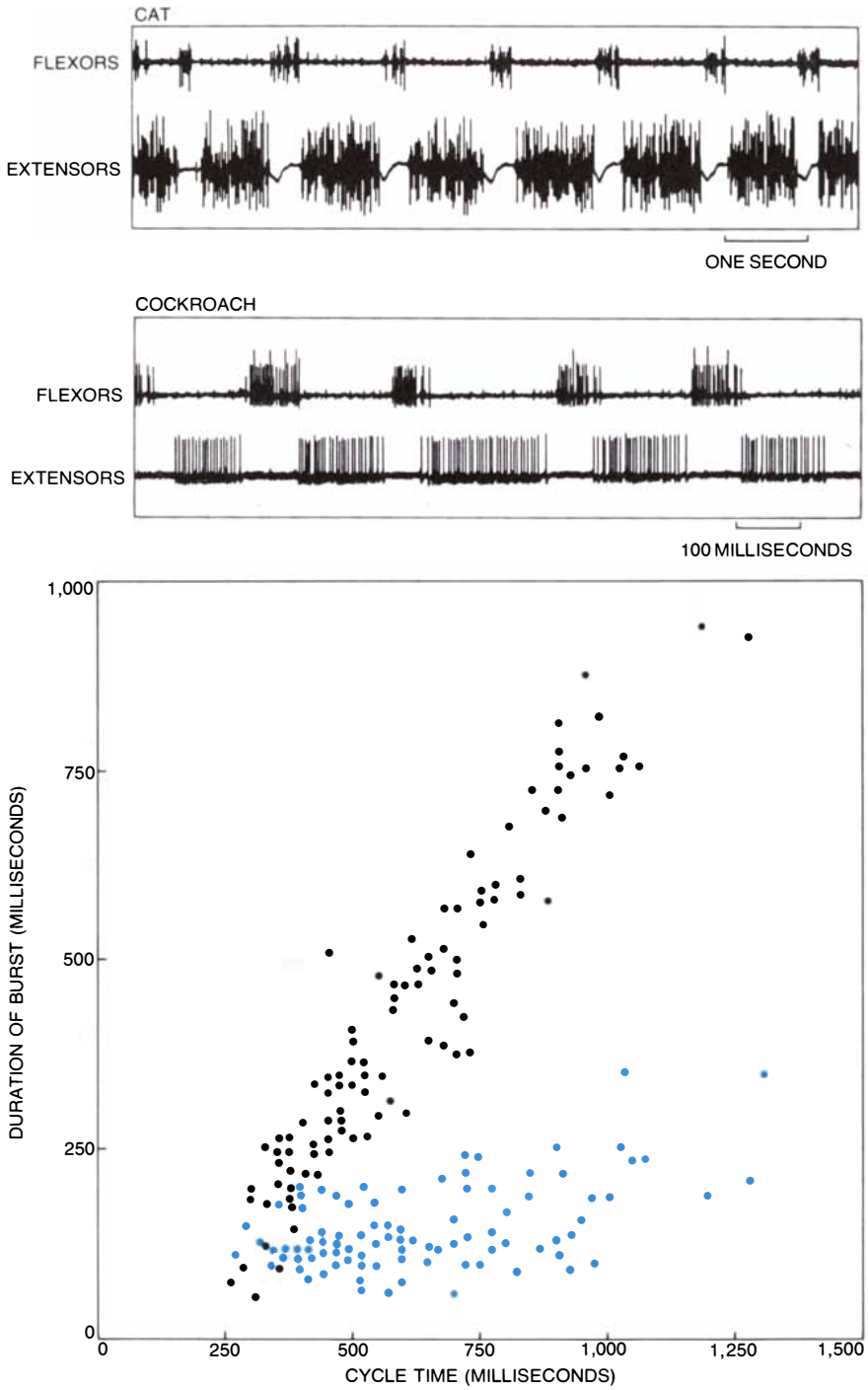
The simplest technique for determining what muscles are involved in giving rise to the swing and stance phases of the step cycle is to record the electrical activity in the leg muscles of a walking animal. Muscle contractions are initiated by a series of brief electric potentials propagated along the external membrane of each muscle fiber. The sum of the electrical events from different fibers can be recorded by means of fine wire electrodes implanted in the muscle. The records obtained by this method are called electromyograms.

To record electromyograms in the leg muscles of a freely walking cockroach the uninsulated ends of two very fine wires (two thousandths of an inch in diameter) are positioned in each of the leg muscles that produce movements around a joint. The other ends of the recording leads are connected to a terminal mounted above the animal, and the lengths of the leads are adjusted so that the animal can walk about freely in an area two feet or so in diameter. The electrical signals from each muscle are then amplified and displayed on an oscilloscope, where they can be photographed. Storing the signals on magnetic tape enables one to do a computer analysis at a later time. To minimize any mechanical effect the recording wires might have on movement, recordings are usually made from only two muscles at a time. It is possible, however, to implant as many as 24 electrodes in a single animal. The technique for recording electromyograms from the muscles in other walking animals is similar in principle to the method developed for the cockroach.

Most of the muscles that account for the movements of the hind legs of the cat and the cockroach can be classified as either flexor muscles or extensor muscles according to whether the function of the muscle is to reduce the joint angle or to increase it. Electromyogram recordings from the muscles during walk-

ing have shown that the electrical activity of the flexors and extensors alternates. The alternating bursts of activity that are observed are well correlated with the movement of the leg. The flexors begin to discharge slightly before the initiation of the swing phase, and the resulting contractions in these muscles rapidly lift the foot from the ground and move the leg forward with respect to the body. In the cat the extensors become active well before the end of the swing phase, causing the leg to straighten near the end of the swing, thereby producing an effective stride. The extensors remain active during most of the stance phase to support the animal's weight and to develop the forward propulsive force. Similarly, in the hind leg of the cockroach activity in the extensor muscles during the stance phase straightens the leg and develops the forward thrust for walking.

In both animals the variations in the amplitude and the times of the onset of electrical activity in the many different flexor and extensor muscles in each leg are complex and depend on the speed of walking. So far little is known about how these complex patterns of electrical activity are created by the central nervous system. The apparently simpler problem of determining the mechanisms responsible for generating the basic alternating pattern of activity in flexors and extensors, however, has received much attention.



EXISTENCE OF A CENTRAL RHYTHM-GENERATOR for each leg of the cat and the cockroach is demonstrated by the fact that even after all sensory input from receptors in the hind legs had been disconnected, alternating rhythmic bursts of electrical activity were generated in the flexor muscles and the extensor muscles in the hind legs of both animals (*traces at top*). The graph at bottom shows that in the cockroach the duration of the centrally generated flexor bursts (*colored dots*) remained constant in contrast to the duration of the extensor bursts (*black dots*). The electrical data are consistent with the behavioral observation that during normal walking the duration of the swing phase of stepping remains comparatively constant.

Within the past few years a great deal of evidence has accumulated to support Graham Brown's original proposal that the basic rhythm for stepping in each leg of the cat is generated by mechanisms within the spinal cord, that in effect there is a central rhythm-generator for each leg. Compelling evidence for the existence of these rhythm-generators comes from the extensive investigations of Sten Grillner and his colleagues in Sweden on the patterns of activity in the flexor and extensor muscles after the elimination of sensory input from the receptors in the legs of walking cats. (Sensory input can be easily eliminated by cutting the dorsal roots: distinct bundles of nerves that enter the spinal cord and contain almost all the sensory nerve fibers from the legs but none of the motor-nerve fibers supplying the muscles.) One of the most important results reported by the Swedish workers was that after the hind-leg segments have been isolated (by cutting either the spinal cord or the upper brain stem) the rhythmic reciprocal patterns of activity in flexors and extensors of the cat's hind leg could still be generated in the absence of sensory information from peripheral receptors in the leg. Moreover, they found that when such "spinal" or "decerebrate" cats were made to walk on a treadmill, the temporal sequence of activation of different hind-leg muscles was not altered by removing sensory input from the hind legs. The latter result showed that in addition to the basic rhythm being centrally generated, central mechanisms are responsible for determining the order in which different muscles are activated.

Similar results were obtained by John F. Iles and me in our investigations of the cockroach. After eliminating all sensory input from the legs of headless animals we found that the reciprocal patterning in hind-leg flexor and extensor motor neurons persists, the sequence of activation of different motor neurons re-

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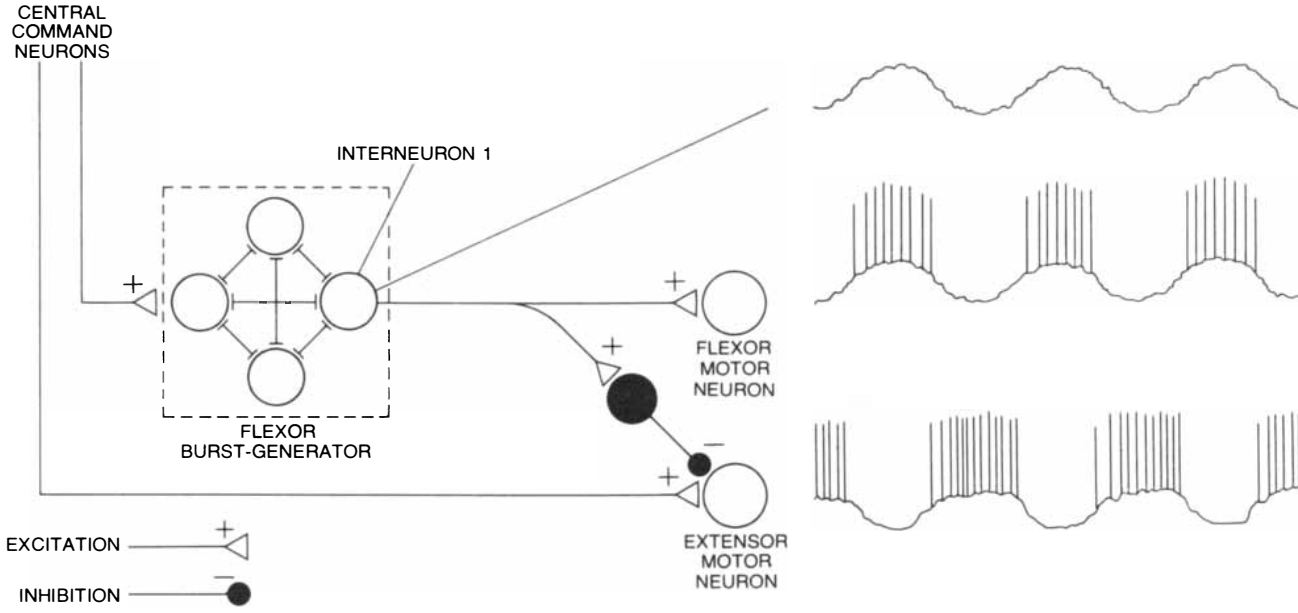


ORGANIZATION of the central rhythm-generating system for each hind leg of the cockroach is outlined here. The interactions of a system of interneurons, called collectively the flexor burst-generator, produce oscillations in the electric potential across the membrane of one of the members of this group of interneurons (*interneuron 1*). These oscillations in membrane potential in turn generate reciprocal bursts of electrical activity in the flexor motor neurons and at the same time inhibit activity in the extensor motor neurons. Diagram assumes that flexor burst-generator and extensor motor neurons are activated by central command interneurons from the brain.

mains the same as that in normal walking animals and the duration of the flexor activity remains fairly constant. Evidently there exist within the lower levels of the cockroach's nervous system networks of nerve cells that can generate the rhythmic sequence of electrical activity in flexors and extensors similar to the activity observed in these muscles during normal walking.

Centrally generated patterns of motor activity have now been found to underlie all kinds of stereotyped behavior in both vertebrate and invertebrate animals; behavior of this type includes respiration, eye movements, chewing, swallowing and flight. Neurophysiologists usually refer to such patterns of activity as motor programs.

The cellular mechanisms responsible for centrally generating rhythmic reciprocal bursts of activity in motor neurons are just beginning to be understood. Little progress has yet been made in determining such mechanisms in vertebrates, primarily because of the immense complexity of the nervous system of these animals. As a result most of our current ideas about the cellular basis of central rhythm-generation have come from studies of invertebrates. In these animals it has been found that the rhythmic activity in motor neurons can be generated in two qualitatively different ways: it can result from intrinsic oscillatory activity in individual nerve cells called pacemakers or it can emerge as a property of an interconnected group of nerve cells none of which have the property of intrinsic oscillation. There is no evidence that in the walking systems of animals pacemaker nerve cells are responsible for generating the rhythmic motor patterns. There is evidence, however, that a group of interconnected nerve cells generates the reciprocal rhythm of activity in the hind leg of the cockroach.

The patterns of activity in cockroach flexor and extensor motor neurons, that is, the nerve cells that give rise to the contraction of the flexor and extensor muscles, led Iles and me to suggest in 1970 that the reciprocal burst activity is generated by a system of interneurons (which we call a flexor burst-generator) that periodically excites the flexor motor neurons and inhibits the extensor motor neurons. Subsequently Charles R. Fourtner and I succeeded in making intracellular recordings with microelectrodes from interneurons within the nervous system of the cockroach during rhythmic leg movements. Our results strongly supported the concept of a flexor burst-generating system. We identified a single interneuron in which the electric potential across the external membrane oscillated in phase with the rhythmic burst activity in flexor motor neurons. When similar oscillations in the membrane potential of this interneuron were artificially created by passing currents through the recording electrode, we were able to mimic the bursts of activity normally generated in the motor neurons during rhythmic leg movements. Moreover, the excitation of the flexor motor neurons was accompanied by inhibition of any spontaneous activity in the extensor motor neurons.

The interneuron exciting the flexors and inhibiting the extensors appears to belong to a network of nerve cells, and the interaction among the members of the network is responsible for the rhythmic activation of the flexors. The interesting feature of this rhythm-generating system in the cockroach is its asymmetry: there does not appear to be a system of interneurons responsible for generating the extensor bursts. The extensors are continuously excited, and their activity is periodically interrupted by inhibition from the flexor burst-generator. The flexor burst-generator gives rise to a burst of electrical activity that is fairly constant in duration, regardless of the rate at which bursts are produced; as a result the duration of the swing phase varies only slightly with walking speed.

Although less is known about how the walking rhythm is generated in the cat's spinal cord, we do know that the rhythm does not depend on direct coupling of motor neurons. As in the cockroach, interactions within a network of interneurons are responsible. A number of different models for how systems of interneurons can give rise to the walking rhythm, including one originally proposed by Graham Brown in 1914, are currently under consideration, but at present there is not enough information to assess the validity of any of them.

The existence of central rhythm-generation for each leg does not mean that sensory input is unimportant in the patterning of motor activity. In fact, sensory input is essential if the animal is

to be able to adapt its stepping movements promptly to compensate for irregularities in the terrain on which it is walking. For example, the stepping of the hind legs of a cat that has undergone either a spinal or a cerebral transection adapts to match the speed of a treadmill for a wide range of treadmill speeds. Since there is little change in the duration of the swing phase, the adaptation of the step cycle to the treadmill speed results from a decrease in the duration of the stance phase. The explanation for this phenomenon is that a sensory signal indicates the completion of leg extension during the stance phase and switches the motor program from stance to swing. Hence following a stereotyped swing phase the foot is placed on the treadmill and moves backward with the speed of the treadmill until a sensory signal triggers the initiation of the next swing phase.

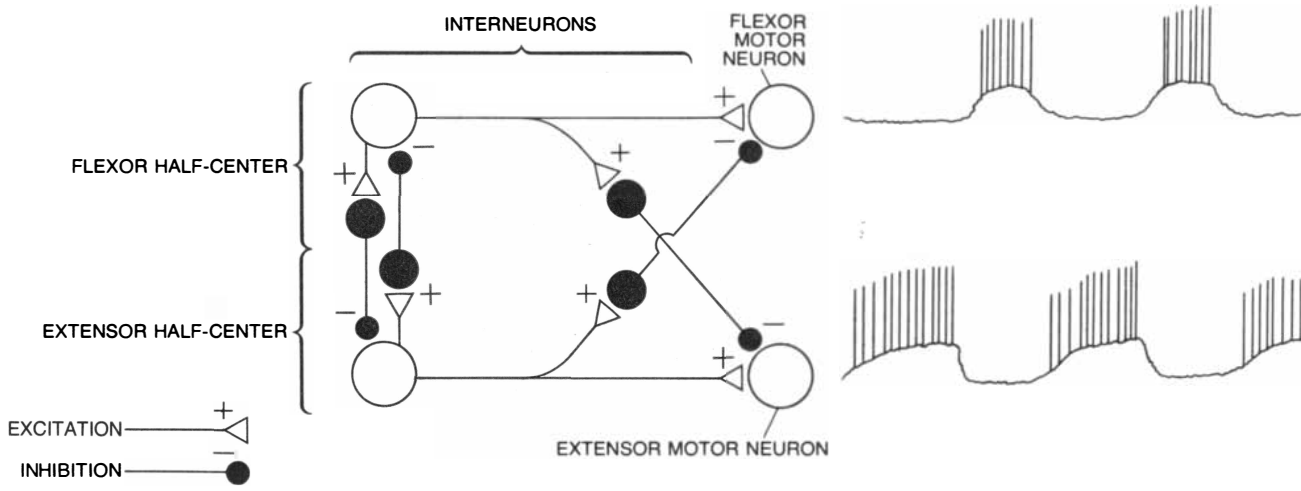
Two conditions seem to be necessary for the swing phase to be initiated. First, the hip joint must be extended; second, the extensor muscles must be unloaded. Both of these conditions are fulfilled near the end of the stance phase. The sensory switching is effected by means of circuits located within the hind-leg segments of the spinal cord. This important conclusion comes from the work of Grillner and his colleagues Serge Rossignol and Hans Forssberg, who showed that preventing extension of the hind leg of a spinal cat walking on a treadmill inhibits stepping in that leg. If the leg is allowed to extend slowly, the swing phase is eventually initiated when the leg is in a position close to the position where swing is initiated during normal walking.

The principle that a leg must be unloaded for swing to be initiated also applies to the walking system of the cockroach. Activation of the receptors that detect forces in the cuticle (the hard external skeleton) of the leg during the stance phase inhibits the flexor burst-generating system of interneurons and thereby prevents the switching from stance to swing. As the leg is extended during the stance phase the stresses in the cuticle diminish, since the animal's weight is carried to a greater extent by other legs. This movement eliminates the inhibitory influence of the cuticle stress receptors from the flexor burst-generator, thus enabling the system to become active and so produce the swing phase.

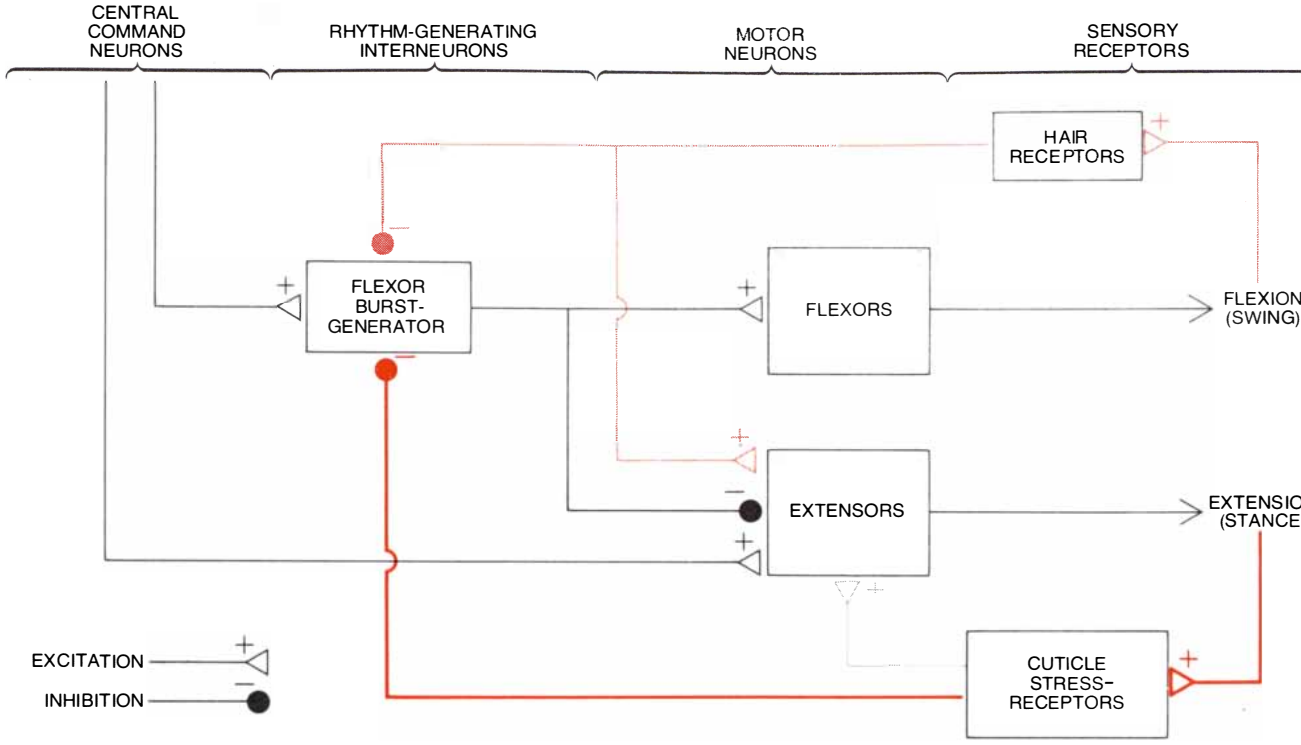
In the cockroach the switching of the motor program from swing to stance is also triggered by a sensory input. A group of hair receptors is excited by flexion movements during the swing phase. The sensory input from these receptors inhibits the flexor motor neurons and the flexor burst-generating system. The latter effect terminates the flexor burst (and hence the swing phase) and enables the leg to initiate the stance phase. The initiation of stance is also facilitated by an excitatory connection from the hair receptors to the motor neurons of the extensor muscle. The inhibitory pathway from the hair receptors to the flexor burst-generator ensures that the leg position at the end of the swing phase remains constant regardless of the position from which the step was initiated.

Apart from the fact that the sensory input functions to switch the motor program from one phase to the other, it is clear that it also functions to modify the motor program during the execution of a single phase. Grillner and his colleagues described a functionally important reflex of this type in the hind leg of a spinal cat. They showed that electrical or mechanical stimulation of receptors in the skin on the top of one of the cat's hind feet during the swing phase causes a large increase in the electrical activity of the leg flexors and as a result the leg is lifted higher. The function of this reflex under natural conditions is easy to see, since the top of the foot will often hit a fixed object. The reflexive elevation of the foot will then enable the foot to avoid the object. A significant feature of the reflex is that it appears in the spinal animal. It follows that this automatic compensation in the step cycle for external perturbations does not necessarily require the participation of higher levels in the nervous system.

In the cockroach feedback from the stress receptors in the cuticle excites the extensor motor neurons during the stance phase. Since these motor neurons are active during the stance phase, the sensory input enhances the amplitude of the extensor activity. The effect can be regarded as a reinforcing reflex; its function is to compensate for variations in load when the resistance to extension unexpectedly changes. For example, if the load carried by the leg is suddenly increased because of irregular movement in one or more of the other legs, there is an increase in the activity of the cuticle stress receptors and thus an increase in extensor activity to resist any tendency of the additional load to decrease the rate of extension. In the cat's hind leg a reinforcing reflex may also function during the stance phase to help compensate for any unexpected increase in the load on the extensor muscles, since increasing the resistance to leg extension during the stance phase causes a marked increase in extensor ac-



HALF-CENTER MODEL for explaining the central generation of rhythmic reciprocal activity in the flexor and extensor motor neurons of the cat's hind leg, originally proposed by the British neurophysiologist T. Graham Brown more than 60 years ago, is presented here in its modern version. According to this view, the flexor and extensor motor neurons, together with their associated driving interneurons, each constitute a "half-center." The two half-centers are assumed to mutually inhibit each other, so that when one is active, the other is inactive. For rhythmic activity to be generated some mechanism is needed to switch the activity from one half-center to the other. One possible switching mechanism would be a comparatively slow intrinsic inactivation of the active half-center, which would have the effect of lessening the inhibition of the other half-center, enabling it to become active. Other models have also been proposed.



REFLEX PATHWAYS in the hind leg of the cockroach are organized to modify the centrally generated patterns of activity in the flexor and extensor motor neurons. During the stance phase of a step stress-receptors in the cuticle of the leg are excited and the input from these receptors inhibits the flexor burst-generator (*dark colored pathway*), thus preventing the initiation of the swing phase until the leg is unloaded at the end of stance. The reflex effect from the cuticle stress-receptors therefore controls the switching of the motor program from stance to swing. Activation of the hair receptors during swing inhibits the flexor burst-generator (*light colored pathway*) near the end of the swing phase, thereby causing the program to switch from swing to stance. This switching is facilitated by an excitatory effect of the hair receptors on the extensors. The cuticle stress-receptors also excite the extensor motor neurons during stance (*gray pathway*); this reflex reinforces central excitatory input to motor neurons. Central command neurons descend from brain.

tivity. This reflex compensation takes a significant amount of time and could function effectively only in a cat that is walking rather slowly.

In brief, it seems clear that reflexes have two quite different functions in controlling the step cycle of a single leg. The first is to switch the motor program from one phase to the other (that is, to initiate the swing phase or to initiate the stance phase) and the second is to modify the motor output within a single phase.

The mechanisms that coordinate stepping in different legs are so far poorly understood. There are evidently three mechanisms that can function to coordinate stepping: (1) direct central coupling of rhythm-generators in each leg by pathways entirely within the nervous system; (2) indirect coupling of the rhythm-generators by a mechanical linkage such that movements of any one leg would alter the sensory influences on the rhythm-generators of the other legs; (3) direct sensory influences communicated from one leg to the rhythm-generators of the other legs. Central inhibitory coupling between adjacent rhythm-generators has been demonstrated during walking in the cat and the cockroach. Following the elimination of all sensory input from the hind legs of spinal cats, the motor activity in opposite legs continues with a rhythmic alternating pattern similar to the one observed during normal walking. In the cockroach, on the other hand, flexor activity in adjacent legs rarely occurs synchronously, even after sensory input has been eliminated.

This observation in the cockroach, combined with an analysis of the electrical activity in the interneurons that connect adjacent segments of the insect, led Iles and me to conclude that adjacent flexor burst-generators mutually inhibit each other by means of central pathways. Mutual inhibitory coupling between adjacent flexor burst-generators explains the behavioral observation that adjacent legs never step at the same time. In addition to the central inhibitory coupling indirect coupling of rhythm-generators by means of mechanical linkages is important in coordinating stepping in the cockroach, particularly when the animal is walking on an uneven surface.

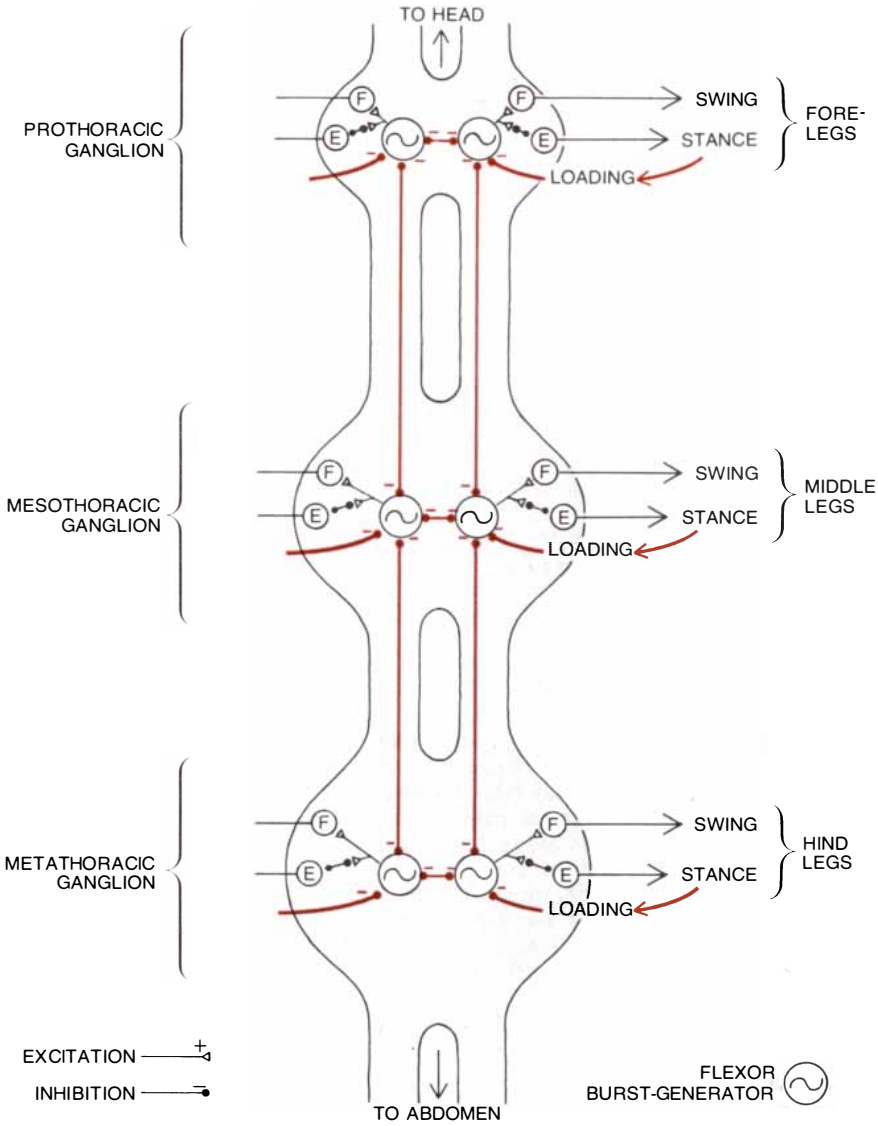
In a walking cockroach the legs that are loaded by the animal's weight are prevented from initiating the swing phase because the activity in the cuticle stress-receptors inhibits the flexor burst-generator associated with each of those legs. The swing phase can be initiated only in the legs that carry little or no load. When a stepping leg finds solid support, it will begin to carry some of the animal's weight and will thus decrease the load carried by one or more of the other legs. This effect may be sufficient to then allow the initiation of the swing phase in the other legs. Subject to the condition that no two adjacent legs can step at the same time (because of the mutual inhibition between adjacent flexor burst-generators), there may not necessarily be any precise and predictable temporal relation between the stepping movements of the different legs when the animal is walking on an uneven surface. The inhibition of the flexor burst-generators by sensory input from cuticle stress-receptors (signaling the load carried by the leg) is an efficient mechanism for enabling the animal to automatically adapt its gait to the terrain on which it is walking, so that the animal can walk stably at all times.

Each flexor burst-generator in the cockroach can be regarded as a simple decision-making element. The decision to be made is whether to initiate a step or not. The flexor burst-generator makes the decision on the basis of information from peripheral receptors signaling the state of that leg and information from other flexor burst-generators signaling the state of adjacent legs. The decision to step is made when the position of all the legs is such that a step will not lead to instability.

The outcome of the recent investiga-

tions into the nervous control of walking in many different animals has been to show that the basic nervous circuits for walking are located in the lower levels of the nervous system. The work on the cat, for example, has confirmed the conclusion of Sherrington and Graham Brown that stepping is an essentially autonomous act depending primarily on nervous circuits within the spinal cord. It appears that an important feature of walking systems in all animals is that the higher centers of the nervous system are not necessary for the basic patterning of motor activity.

This does not mean that the higher centers play no role in the control of walking. They are certainly involved in the initiation and maintenance of walking, but the pathways that convey the commands for walking from them have not yet been identified. Another important function of the higher centers, particularly in mammals and birds, is to modulate the basic walking motor program in response to sensory inputs from receptors in the head, such as the eyes and the vestibular apparatus (the receptor organ in the ear that senses the position and motion of the head). The modulation of the motor program by inputs from the receptors in the head presumably functions not only to control the direction of walking but also to help ensure that balance and stability are maintained at all times.



STEPPING IS COORDINATED in the six legs of a walking cockroach by means of the nervous pathways sketched here against the background of the insect's thoracic nerve cord (*gray*). For each leg there exists within the thoracic nerve cord a flexor burst-generator, which when active excites the flexors to produce the swing phase. Adjacent flexor burst-generators mutually inhibit each other; as a consequence no two adjacent legs can step at the same time. The existence of such pathways explains the basic alternating pattern of stepping in adjacent legs. An inhibitory input from the cuticle stress-receptors to the flexor burst-generators prevents any leg from stepping when it is loaded during stance (*red pathways*), thereby providing a mechanism for adapting the pattern of stepping when animal is walking on uneven surface.

There are two further striking similarities between the mechanisms responsible for the control of walking in the cat and those responsible in the cockroach. The first is that the basic reciprocal rhythm of electrical activity in flexors and extensors can be generated in the absence of sensory input from receptors in the legs. Moreover, in both animals the duration of the centrally generated flexor bursts is fairly constant compared with the variation in the duration of the extensor bursts. This finding corresponds to the behavioral observation that the duration of the swing phase remains essentially constant for large changes in walking speed.

The second similarity is that reflexes function to switch the motor activity from extension to flexion. The initiation of the swing phase requires that the leg be extended and unloaded. Reflexes can also function to modulate the motor activity within either the swing phase or the stance phase. Both types of reflex function to modify the motor program in order to adjust the stepping movements to unpredictable variations in the external environment. It is also important to note that these reflexes can function in animals after the higher levels of the nervous system have been disconnected. Thus automatic adaptation of the stepping movement to the environment is partly achieved by reflex pathways confined to the lower levels of the nervous system.

At first the marked similarities between the basic mechanisms for the control of walking in the cat and those for the control of walking in the cockroach may seem surprising, particularly when it is considered that mammals and insects evolved separately from nonwalking wormlike ancestors. The similarities become more understandable, however, when it is remembered that in both groups of animals the walking system evolved for the same function, namely to move the animal rapidly and stably over uneven terrain. There are numerous examples in nature where evolutionarily unrelated animals rely on similar mechanisms for the same task: witness the similarity of the eye of cephalopod mollusks, such as the octopus, and the eye of vertebrates. The similarity of the walking systems in the cat and the cockroach suggests that the number of ways of optimally constructing a walking system is quite limited.

From the study of walking in diverse animals there are clearly beginning to emerge some common principles underlying the control of walking. A better understanding of these principles may in turn contribute to a better understanding of how the nervous system controls walking in man.

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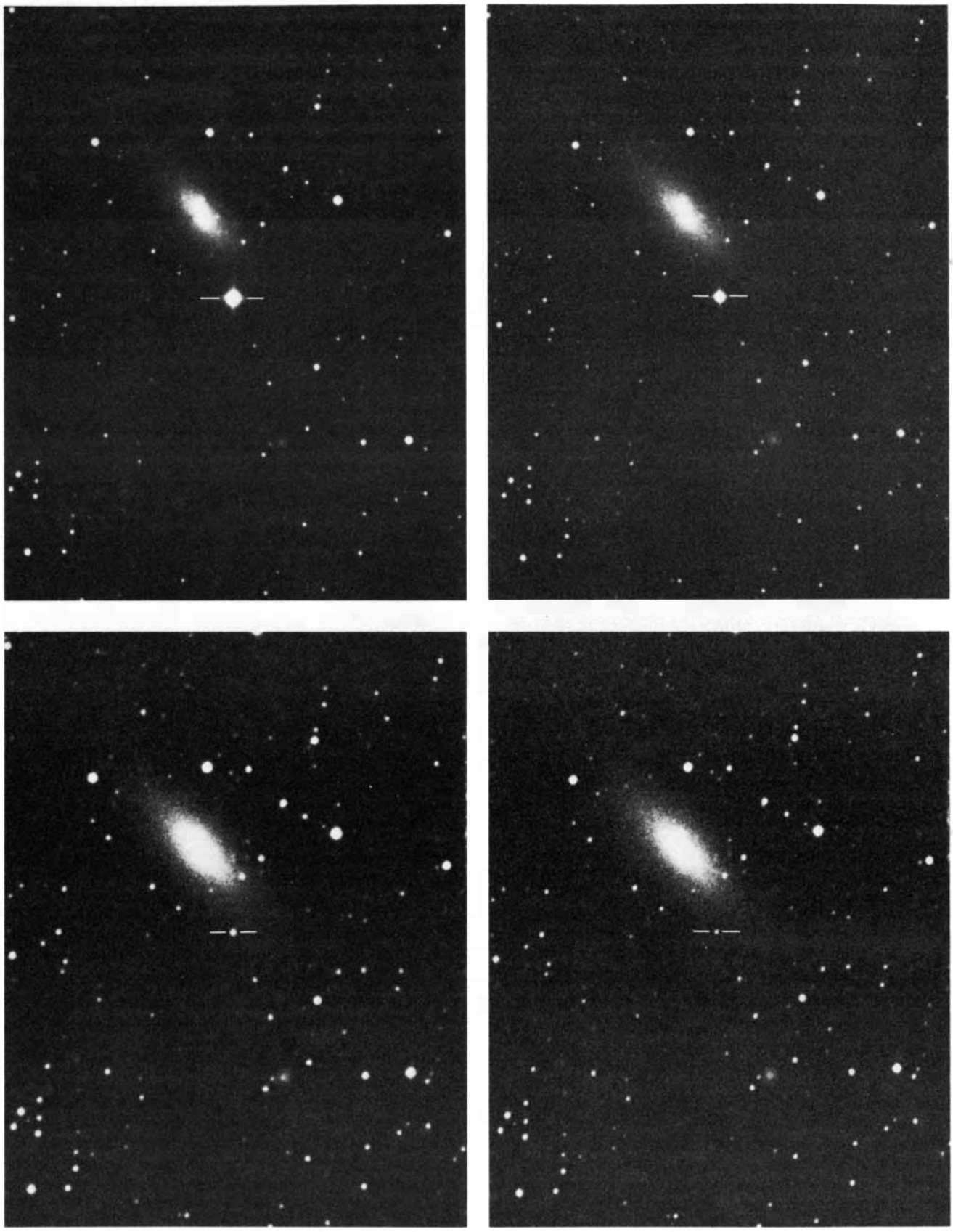


SUPERNOVA EXPLODING in the galaxy NGC 5253 was so powerful that for a few weeks it was as brilliant as all the rest of the stars in the galaxy combined. It was discovered in May, 1972, and was photographed with the 48-inch Schmidt telescope on Palomar Mountain by Charles T. Kowal of the California Institute of Technology. The supernova was the fifth to be discovered in an external galaxy in 1972, so that it was designated SN 1972e. The sequence of photographs, which reads from left to right and top to bottom, was made over a period of nearly a year as the brightness of the star declined from May 16, 1972 (*top left*), through April 24, 1973 (*bottom right*). The spectrum of the object indicates that it was a Type I supernova, the explosion of a star with about the same mass as the sun.

Supernovas in Other Galaxies

These stellar cataclysms occur about once every 50 years in a galaxy. Therefore the nature of supernovas can best be investigated in galaxies outside our own

by Rober P. Kirshner

A supernova, the catastrophic explosion of a massive star, is believed to occur in a galaxy about twice a century. The last supernova visible from the earth in our own galaxy was seen in 1604, five years before the telescope was first turned on the sky. Since thousands of galaxies are visible from the earth with large telescopes, however, on the average one may expect to see a supernova in one galaxy or another once every few months. Indeed, in observatories around the world there are astronomers monitoring the sky for the appearance of such stellar explosions in distant galaxies—explosions that for a few weeks may outshine all the rest of a galaxy's billions of stars combined.

Nearly 400 extragalactic supernovas have been observed over the past 90 years. Such observations have helped to make it possible to develop a complete picture of the life cycle of stars. It is believed by most astrophysicists that a supernova is a violent explosion that disrupts a star and ends its life as a normal star. Some supernovas may leave behind cosmic ashes in the form of a neutron star or a black hole. It has also been suggested that the tremendous heat and pressure generated in the explosion synthesize new elements and then expel them into the interstellar gas of a galaxy, and that perhaps supernovas are the origin of the cosmic rays that steadily bombard the earth. It has been imagined further that the energy released by the supernovas is somehow related to such exotic and powerful extragalactic energy emitters as the Seyfert galaxies and the quasars.

The first, and the brightest, supernova seen in an external galaxy first became visible in 1885. In August of that year a new star suddenly appeared in the central region of our neighboring galaxy the Great Nebula in Andromeda. The star brightened rapidly until it reached the seventh magnitude: just a little fainter than the faintest star visible to the unaided eye. At that time it was not even known whether the Andromeda nebula and similar nebulas were objects within our galaxy or were separate systems of stars outside it. Ordinary novas, the fairly common stellar explosions in which a star brightens by a factor of perhaps 10,000, were well known in 1885. It was assumed that the new star in the Andromeda nebula was an ordinary nova, and this assumption provided an estimate for the distance of the nebula that placed it well within the confines of our galaxy.

In the 1920's the work of Edwin P. Hubble on variable stars in the Andromeda nebula and other spiral nebulas proved that such systems were at great distances from our own galaxy. Only then was the real nature of the new stars seen in those systems recognized. Once it was realized that the distance to the Andromeda nebula was not merely thousands of light-years but hundreds of thousands the extraordinary luminosity of the supernova of 1885 became clear. That star had been not just 10,000 times more luminous than an ordinary star but more like 10 billion times more luminous.

Even after the spiral nebulas were firmly established as external galaxies and the magnitude of the supernovas within them was recognized, no systematic study of supernovas in other galaxies was undertaken until Fritz Zwicky of the California Institute of Technology began to search for them in 1934. Using a camera with a lens 3¼ inches in diameter mounted on the roof of the astronomy building at Cal Tech, he repeatedly photographed a rich cluster of galaxies in the constellation Virgo. Afterward he carefully examined the photographs for new stars. In September, 1936, he expanded his work with an 18-inch Schmidt telescope that had just been set up on Palomar Mountain. Over the next three years Zwicky discovered 12 supernovas in other galaxies, compared with 21 that had been accidentally discovered over the preceding half century. For each supernova Zwicky, in collaboration with Walter Baade and Rudolph Minkowski, recorded the change of the star's brightness over a period of time and analyzed the star's light spectroscopically.

Zwicky's work in surveying distant galaxies for supernovas was as remarkable for its motivation as for its productivity. Even before he began his systematic observational work in 1933 he had predicted that the supernova outbursts were stars that were collapsing to become neutron stars. This prediction he made only two years after the discovery of the neutron. Furthermore, he contended that as the stars collapsed their composition was altered and that they emitted cosmic rays. The succeeding 44 years have shown that Zwicky's intuition was certainly directed toward the right questions, although even today the answers are still not clear.

Working with the 18-inch Schmidt telescope on Palomar in 1937, Zwicky discovered an eighth-magnitude supernova in the nearby irregular galaxy IC 4128. Minkowski immediately undertook a series of spectroscopic observations of the supernova, observations that provided the bulk of the spectroscopic information on supernovas until as recently as 1972. In that year another bright supernova was discovered by Charles T. Kowal of Cal Tech in the nearby irregular galaxy NGC 5253. It was designated SN 1972e, for the fifth supernova to be observed in 1972. Much of the information about supernovas that has been gained since Minkowski's work is based on data secured from this bright supernova with modern observational techniques.

The system for searching for supernovas today is for the most part not very different from the one employed by Zwicky. A set of regions in the sky is chosen, generally on the basis of how many galaxies in each region are close enough to our galaxy for supernovas within them to be detectable. Night after night, month after month, the same regions are repeatedly photographed. The photographic plates are superposed or are laboriously scanned in pairs with a blink microscope, which reveals if a new star has appeared on one of the plates. If a suspected new star is found,

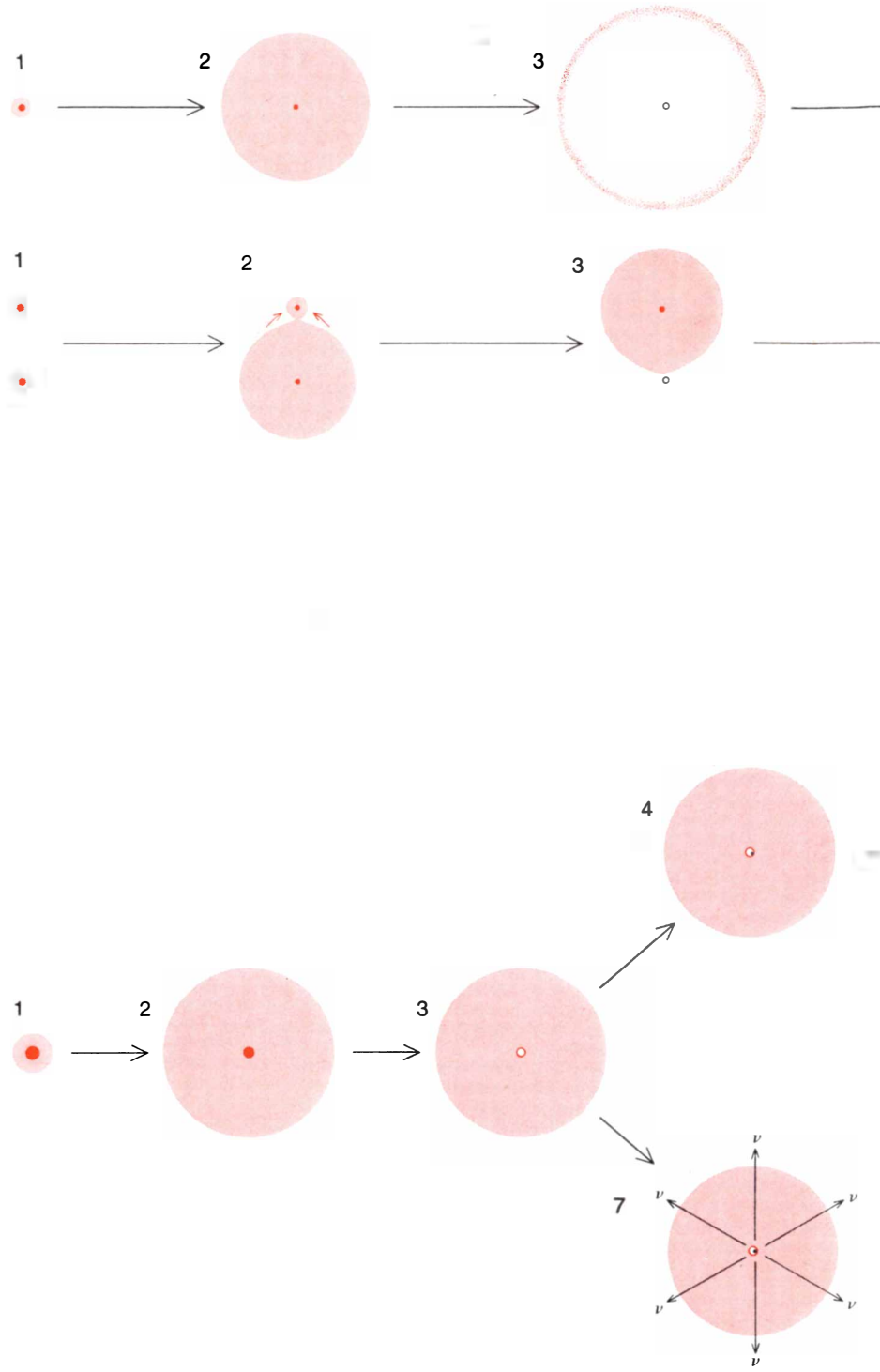
as one is once every few months in a typical search, the photograph is usually repeated to be certain that a grain of dust on the plate or a microscopic defect in the emulsion has not been mistaken for a stellar cataclysm.

When the observer is certain that the object detected is real, he measures its position, estimates its brightness and sends a message by telegram or telephone to the Central Bureau for Astronomical Telegrams in Cambridge, Mass. From Cambridge telegrams with the relevant information in code are dispatched to observatories around the world. Interested astronomers at other observatories then decode the telegram and can begin their own observations of the supernova.

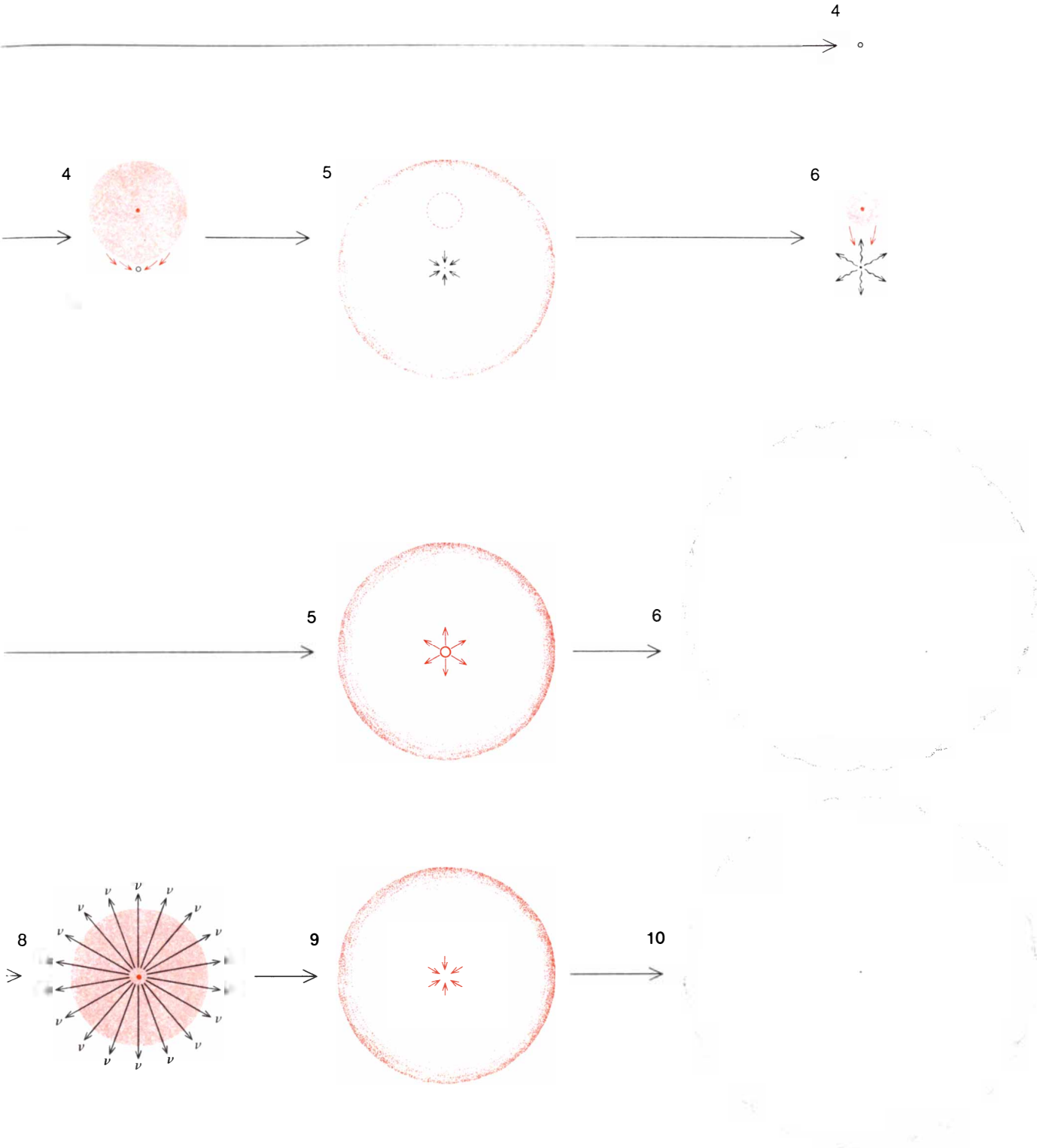
The system is not perfect. The time required for the original observer to make the photograph, examine the plate for a supernova and repeat the observation on the next clear night can be several days. The telegram sent to other observatories from Cambridge may arrive on a weekend or at night, when no one is there to receive it. When a supernova explodes, however, its brightness usually increases quite rapidly. Since our response to supernovas is somewhat sluggish, relatively few supernovas have been observed before they have attained their maximum brightness. And that early period of their development is potentially of major importance to the gaining of an understanding of the nature of supernovas.

The techniques by which galaxies are monitored for supernovas are being improved. One example is the real-time search program conducted by Justin Dunlap at the Corralitos Observatory of Northwestern University near Las Cruces, N.M. A 24-inch reflecting telescope is programmed to move rapidly and automatically through observations of a sequence of galaxies. An exposure of a few seconds with a television camera generates a picture of each galaxy on a television screen in the observer's room. The observer compares the image with a reference image, decides whether or not any new star has appeared and then has the telescope proceed to the next galaxy.

In Dunlap's real-time search program hundreds of galaxies can be checked each night, and the results are immediately known. The galaxies chosen are close enough for any supernova in them to be easily detectable before it reaches its maximum brightness. The efficiency of the system was demonstrated in January, 1975, when Dunlap discovered a supernova in NGC 2207 six days before it attained its maximum brightness. During that period the supernova was closely monitored by Halton C. Arp on Palomar and by me at the Kitt Peak National Observatory in Arizona. It is clear that the future of supernova searches



EVOLUTION OF A SUPERNOVA is different for stars of different masses. A star only a few times as massive as the sun (*top row*) fuses hydrogen into helium in its core (*dark color*) in a stable manner for several billion years (*1*). After most of the hydrogen is exhausted the core of the star contracts while the exterior of the star expands, and the star becomes a red giant (*2*). Eventually the outer layers of the red giant are puffed away by the star as a planetary nebula (*3*), such as the Ring Nebula in the constellation Lyra, leaving behind a stable white dwarf (*4*). It is believed that Type I supernovas are members of double-star systems (*second row*), where their early evolution (*1 and 2*) is the same as the evolution of their solitary counterparts. When they reach the white-dwarf stage (*3*), however, matter is transferred suddenly from the companion star (*4*), adding matter to the white dwarf and pushing its mass past the critical limit of 1.44 solar masses. At that point the core of the white dwarf collapses violently, releasing energy



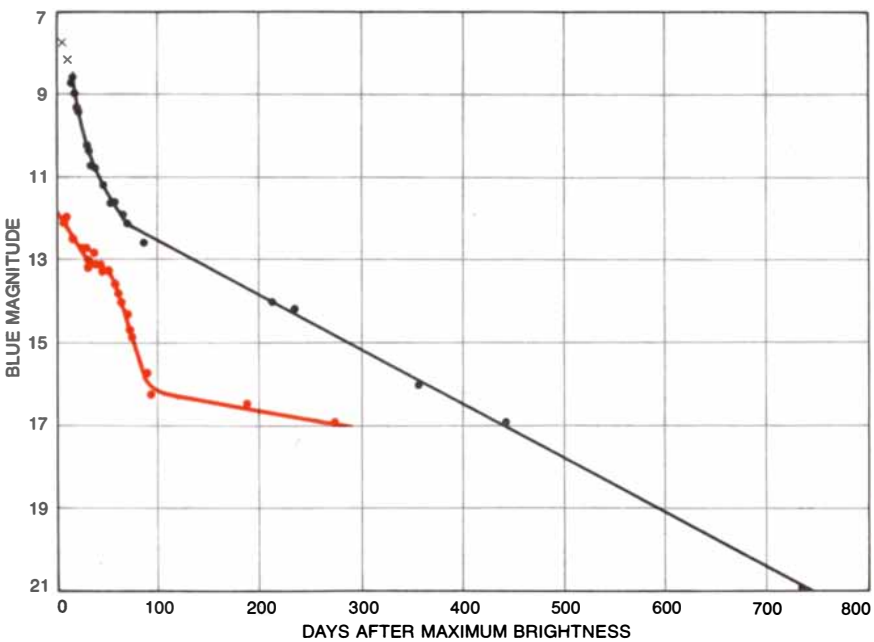
as a supernova (*5*) and leaving behind a binary system composed of an ordinary giant star and an X-ray source (*6*). For a star much more massive than the sun (*third and bottom rows*) the evolution of a supernova is different. Such a star also fuses hydrogen into helium in its core for a few hundred million years (*1*), and when the hydrogen is nearly exhausted, the core contracts, the outer layers of the star expand and the star becomes a red giant (*2*). Hydrogen continues to be burned in a shell (*dark color*) around the core as the core itself contracts until it heats up enough to fuse helium (*white*) into carbon (*3*). When the helium is nearly exhausted, the core begins to burn the carbon. At that point one of two catastrophes can befall the star. The ignition of the carbon (*black*) itself (*4*) could induce instabilities that would detonate the star as a supernova of Type II (*5*), leaving behind nothing but an expanding gaseous remnant (*6*). Or, if the carbon is safely ignited, the extraordinarily high temperatures in the core could generate neutrinos (*ν*) at an ever increasing rate (*7 and 8*), sapping the star's energy and causing its core to plunge headlong into total collapse. In this case a final burst of neutrinos might carry away so much of the red giant's rotational momentum that it would blow off the entire outer envelope of the star. An explosion of this kind (*9*) would leave behind a gaseous remnant, in the center of which would be a pulsar (a rapidly rotating neutron star) or a black hole (*10*).

lies with detection systems that are semiautomatic or even fully automatic.

In the past when a supernova has been discovered and word of its existence has been circulated, the interested investigator has had to face a difficult choice: should he obtain photometric data, that is, quantitative measurements of the brightness of the object as seen through a series of standard filters? Or should he obtain spectroscopic data, that is, measurements of the relative intensity of the star's light over a range of wavelengths? Generally speaking, precise photometric data can be got quickly and easily; spectra take more time but are richer in information. In practice the observer's choice is often determined by the instruments that are attached to the telescope at the time the announcement of the supernova reaches the observatory.

In recent years several supernovas have been observed with the 200-inch telescope on Palomar with the aid of a new instrument that combines the precision of photometry with the detail of spectroscopy. The instrument, designed by J. Beverley Oke of Cal Tech, is a multichannel spectrophotometer. Inside the spectrophotometer are 32 photomultiplier tubes that can rapidly measure the brightness of a supernova in each of 100 or more narrow bands of wavelengths. The bands range in width from 20 to 360 angstroms; the instrument is sensitive to the entire range of wavelengths from 3,100 angstroms in the ultraviolet to 11,000 angstroms in the near infrared. The data obtained with the instrument by Arp and Oke, together with Leonard Searle, Michael Penston, Jesse L. Greenstein and James E. Gunn, provide the basis for much of the knowledge of supernovas that has recently been gained.

It has been known since Minkowski's work in the 1940's that supernovas can be divided into two classes based on their spectra; the two classes are designated Type I and Type II. Supernovas of Type I form a fairly homogeneous group with relatively little variation between the spectrum of one star and that of the next. They are the only type of supernova found in elliptical galaxies, which are believed to be very old and which are known to have few, if any, stars more massive than the sun. Thus supernovas of Type I are assumed to be the explosion of a star of about one solar mass. If a Type I supernova is observed photometrically through the standard *B* filter of blue light, it is seen to rise to its maximum brightness in several days, to remain there for several more days and then to decline rapidly for about 30 days. After that a Type I supernova fades in a curve that is almost exactly exponential. Near the maximum brightness the spectrum of such a supernova is distinguished by a strong absorption line of ionized silicon at the wavelength of 6,150 angstroms.



LIGHT CURVES OF SUPERNOVAS of Type I (*black*) and Type II (*color*) are quite different. The light curves are a graph of the supernova's decline in brightness, measured in terms of the logarithmic scale of magnitudes (each magnitude represents a factor of about $2\frac{1}{2}$ times in brightness), plotted over a period of hundreds of days. The light curve of the Type I supernova SN 1972e shows a steep decline in brightness followed by an almost perfect exponential decay. Such behavior is typical of a Type I supernova. The light curve of the Type II supernova SN 1970g, which was discovered in the galaxy M101, shows a much more complex pattern. Dots represent actual observations. They were made photometrically through standard blue filter. Here Type II supernova was fainter than Type I, but that is not necessarily the case.

Supernovas of Type II constitute a much less homogeneous group than those of Type I. They are found principally in the arms of spiral galaxies, which are rich in massive young stars. It is hence assumed that a Type II supernova is the explosion of a star far more massive than the sun. That assumption seems to be confirmed by spectrometric measurements of the strength of the emission lines of hydrogen in the ejected material, which indicate that the mass of the ejecta is equal to at least one solar mass. If a typical Type II supernova is observed photometrically through the standard *B* filter, it is also seen to rise rapidly to maximum brightness, remain there briefly and then decline rapidly for roughly 25 days. Its further decrease in brightness, however, is not exponential. Instead its brightness declines to a plateau where it remains for between 50 and 100 days. Then it declines even more steeply. Near the maximum brightness of a Type II supernova the spectrum of the star is distinguished by a strong emission line of hydrogen at the wavelength of 6,563 angstroms.

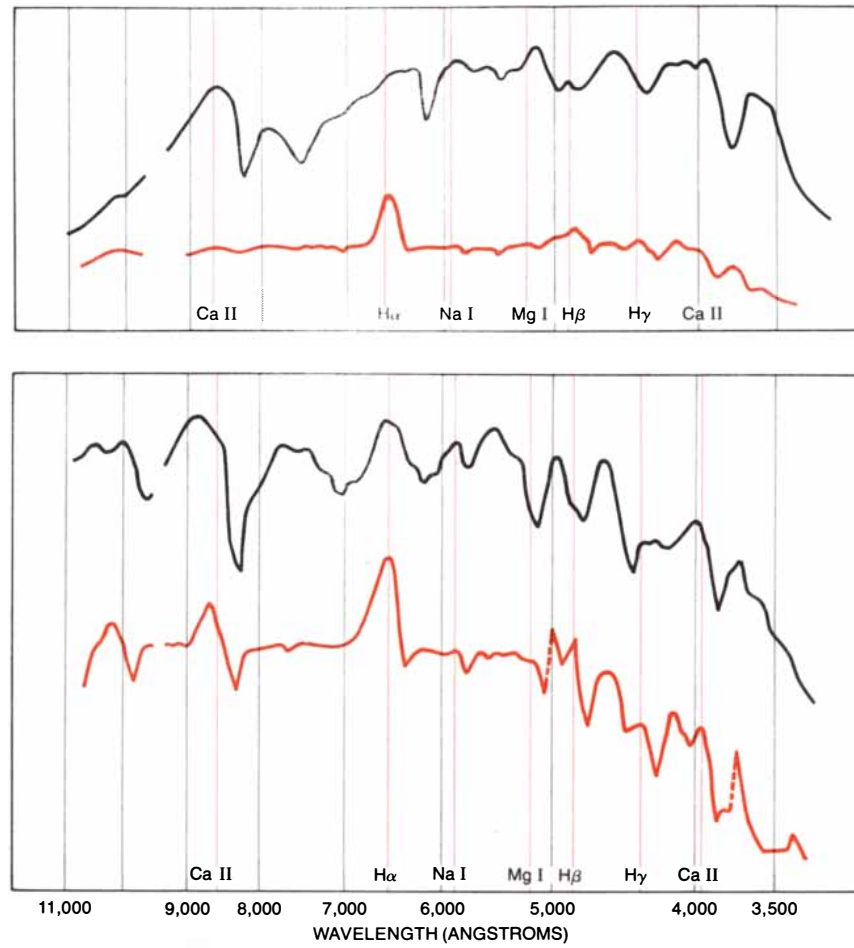
If supernovas of Type I and Type II arise from very different kinds of stars, why are the early parts of their light curves so much alike? Moreover, what is physically happening inside the star as the supernova develops? Why should a star with a mass as small as that of the sun, which could settle down as a stable white dwarf, explode so catastrophically? Spectrophotometric observations of a handful of supernovas in other galaxies have yielded a wealth of information about the actual temperature, velocity and composition of the supernova ejecta, information that makes the behavior of each type of supernova more comprehensible.

Because the distribution of energy in Type II supernovas is simpler than that in Type I supernovas I shall take up the Type II's first. A representative Type II supernova for which there are good data is SN 1970g, which was seen to explode in the galaxy M101 late in 1970. Spectrophotometric scans of the object's spectrum show that it evolved over a period of months. In the early phases of the outburst the overall distribution of the star's energy closely matched the smooth distribution of energy characteristic of a theoretical black body at a temperature of 12,000 degrees Kelvin. Now, the energy emitted per unit area by an efficient incandescent radiator, which behaves as a black body, is determined only by its temperature. Furthermore, one can measure the flux of radiation received from the supernova at its maximum brightness. Thus if the distance to the supernova is assumed or is known from other measurements, a combination of the temperature and the observed flux of radiation can yield an estimate of the star's radius at the time

of its maximum brightness. For SN 1970g the radius was 3×10^{14} centimeters, a radius as large as that of the orbit of the planet Uranus.

Once the radius of the supernova is known its absolute luminosity can also be determined. For SN 1970g the luminosity was 10^{42} ergs per second, a billion times the luminosity of the sun. Even more interesting, data from spectrophotometry and from standard broad-band photometry enable one to plot the supernova's change in radius with respect to time. For some 30 days after the star's initial explosion the radius of the surface from which the visible light is emitted expands at a nearly constant velocity of 5,000 kilometers per second. At the end of that time the star's photosphere, or visible surface, has attained a radius of some 2×10^{15} centimeters, a radius much larger than that of the solar system. As the photosphere expands, its temperature decreases to about 6,000 degrees K. After reaching its maximum extent the photosphere, which up to then is opaque, is so thin that it begins to become transparent. Thus the apparent radius of the star begins to shrink, giving rise to the rapid decline in the light curve of a Type II supernova.

Plausible theoretical models of Type II supernovas have been developed by W. David Arnett and Sidney W. Falk of the University of Texas and independently by Roger A. Chevalier of Kitt Peak. The models completely ignore the cause of a supernova's explosion but closely reproduce its observed effects. They assume instead that regardless of the details of what is going on deep inside the star the explosion clearly heats and accelerates the star's outer layers. Arnett and Falk and Chevalier consider only the effects of the shock wave resulting from the explosion as it travels from the center of a plausible model star through the star's outer layers. The model stars they have chosen are very extended red supergiants: stars with a mass several times that of the sun and with a volume millions of times greater. Such extended red supergiants are at the very end of their life cycle as generators of thermonuclear energy.



SPECTRA OF SUPERNOVAS of Type I (*black*) and Type II (*color*) also differ. The curves plot intensity of radiation with respect to wavelength. Peaks are regions in the spectrum where energy is being emitted; troughs are regions where energy is being absorbed. The top pair of curves compare the spectra of SN 1972e (*black*) and SN 1970g (*color*) shortly after they attained maximum brightness; the bottom pair of curves compare their spectra a month later. The spectrum of each supernova also evolves with time. The spectral lines identified are the following: *Ca II* is singly ionized calcium. *Hα*, *Hβ* and *Hγ* are all emitted by transitions of electrons in hydrogen atom. *Na I* is un-ionized sodium, *Mg I* un-ionized magnesium.

The model supernovas have two very important characteristics that agree well with the characteristics of observed supernovas. First, calculations show that extended red supergiants are already so large that they do not cool significantly as they expand to become roughly the size of the solar system. Second, the interior of an extended red supergiant is a large region of nearly constant density; therefore an explosion in the center of the star transmits its energy to the surface efficiently. Hence the model predicts that the energy released in the center of the star can appear as the heat and motion actually observed at the surface of a supernova. The model further predicts that the supernova should have a temperature of about 10,000 degrees K. at the surface and should expand at a velocity of about 5,000 kilometers per second shortly after it attains its maximum brightness. The fact that the calculations based on models of stars that seem likely to explode agree so well with the observations of stars that actually explode is encouraging. Conversely, the fact that the agreement comes from considerations having to do with the structure of the star's interior and not from calculations of the details of the explosion means that spectrophotometric data from a supernova during the first month of the outburst can yield little direct information on the source of the energy released in the star's core.

How do the observations and the theory of Type II supernovas compare with those of Type I supernovas? A well-observed representative of Type I supernovas, SN 1972e, was discovered by Kowal in NGC 5253. Spectrophotometric observations were obtained with both the multichannel spectrophotometer on the 200-inch telescope and with a simpler scanner coupled to the 60-inch reflector on Palomar. Both series of scans showed that the overall energy distribution of a Type I supernova is not much different from the energy distribution of a Type II. Unlike the background continuum in the spectrum of a Type II supernova, however, even in the earliest days after the explosion, the continuum of this Type I supernova was not smooth. It was distorted by very broad features both in emission and absorption. Nevertheless, the overall energy distribution of the spectrum roughly corresponded to that of a black body at a temperature of 10,000 degrees K. Just as for a Type II supernova, this Type I supernova quickly cooled as its photosphere expanded. The cooling decreased the energy in the ultraviolet region of the spectrum more rapidly than that in the infrared, until the photosphere reached a temperature of about 6,000

degrees. Then the star proceeded to get fainter while remaining at a constant temperature as the star's visible surface began to shrink. That was the point where the supernova's brightness began to decrease exponentially.

For both types of supernova the study of the light distribution in the continuous background of the star's spectrum provides important clues to the correct identification of the lines in the spectrum. The temperature derived from matching the continuum to the spectrum of a black body at a certain temperature is a guide to the types of spectral lines that might be expected. In the spectra of Type II supernovas strong lines of hydrogen are seen. In addition there are strong lines of emission and absorption from ionized calcium and un-ionized sodium and magnesium, and a blend of lines due to ionized iron. The strength of the lines indicates that the relative abundance of these elements in the supernova is not very different from their abundance in the sun. If supernovas synthesize heavy elements out of lighter ones in the course of their explosion, none of that material is initially seen in the rapidly expanding debris.

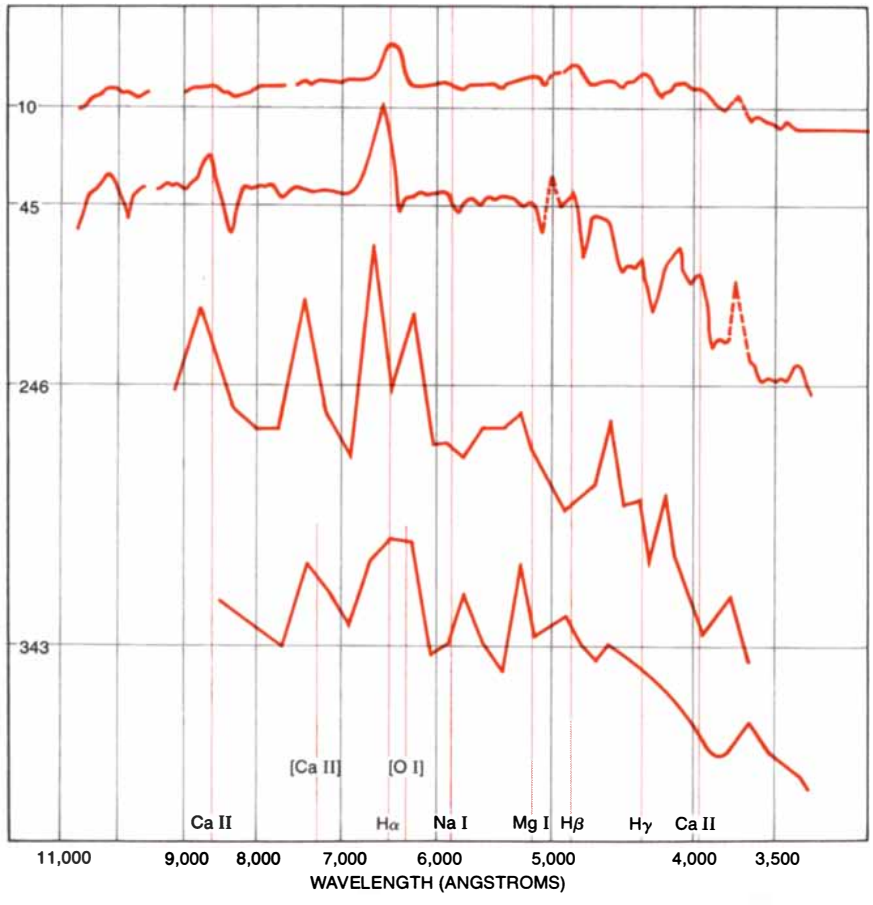
The spectra of Type I supernovas are more difficult to analyze. In fact, it is not universally agreed whether the observed spectrum of a Type I supernova is chiefly composed of emission lines, absorption lines or both. It seems likely, however, that the broad emission features that characterize the spectra near the maximum brightness of the star correspond to many of the same atoms and ions seen in both emission and absorption in the spectra of Type II supernovas. Perhaps the fact that the lines distort the background continuum of the spectra can be explained if the abundance of those elements with respect to the abundance of hydrogen has been enhanced, either during the presupernova evolution of the star or during the explosion.

The spectra of Type I supernovas change qualitatively just at the point in the light curve where their decline in brightness becomes exponential. Before that exponential decline the flux from the continuum dominates the spectra, and the individual emission and absorption lines are superposed on the continuous background. After the exponential decline sets in, however, the continuum is relatively unimportant and the spectrum is dominated by a group of four strong emission lines.

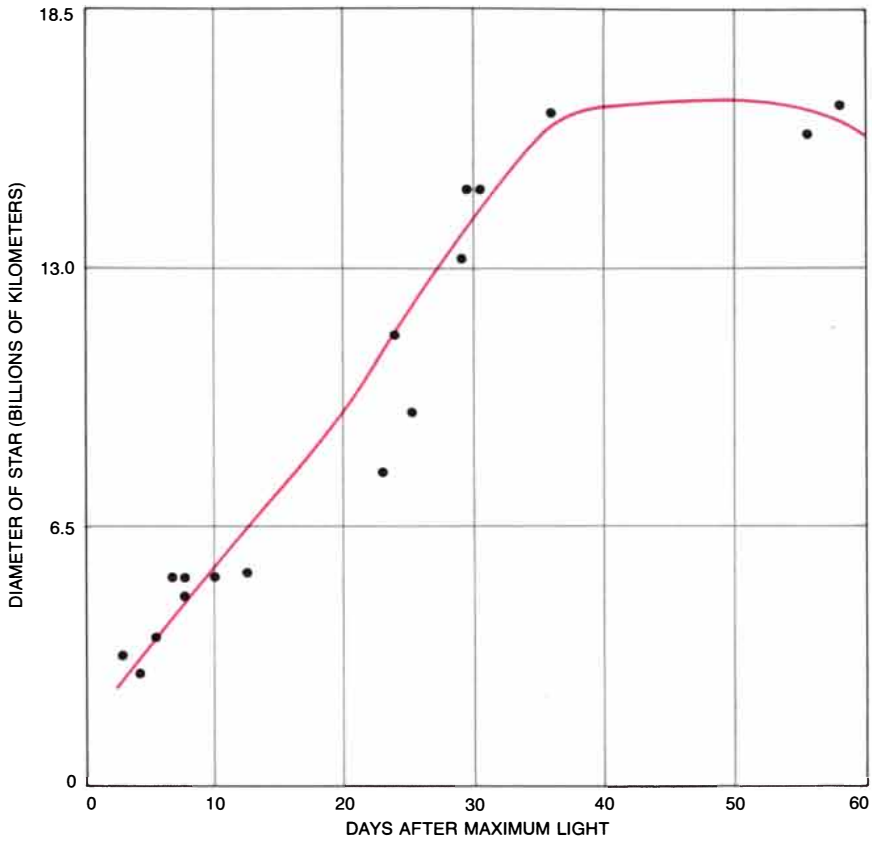
Two explanations have been advanced to account for these lines. Philip Morrison of the Massachusetts Institute of Technology and Leo Sartori of the University of Nebraska have suggested that the emission lines result from the fact that at one point in the explosion of the supernova the star emits a huge pulse of ultraviolet radiation. The visible light seen from the earth would then be emitted by helium atoms around the star the ultraviolet radiation has caused to fluoresce. This suggestion predicts that there should be a strong emission line of helium at the wavelength of 4,686 angstroms and that the intensity of the line would decline exponentially over a long period of time. Whether a Type I supernova actually emits such a pulse of ultraviolet is not yet known, and it is also not known whether the gas surrounding the star has the properties that would be needed to account for the fluorescence.

The second explanation of the emission-line spectrum of Type I supernovas comes from an attempt to identify the origin of the four strong lines. Oke and I have suggested that the features are created by a blending of lines emitted by ionized iron. The sum of the 216 lines of iron that are most likely to be emitted by the exploding material has a strong resemblance to three of the four strong emission lines observed in the spectra of Type I supernovas. The fourth line, at a wavelength of 4,600 angstroms, is, however, the strongest one. Charlotte Gordon of the Thomas J. Watson Research Center of the International Business Machines Corporation has suggested that this line may be due to doubly ionized iron. If our identification of the lines is correct, the amount of iron in the gaseous envelope ejected by a Type I supernova is 20 times the mass of iron in the sun. If a Type I supernova is the explosion of a star with about the same mass as the sun, our interpretation requires that the ejecta be substantially enriched in iron.

Even if our identification of the lines is not correct, the fact that during the time when the supernova is decreasing exponentially in brightness its spectrum shows emission lines means that energy must still be flowing into the ejecta. If no energy were flowing into them, the energy radiated by the gas at the wavelengths of the emission lines would rapidly cool the ejecta and the emission lines would quickly fade. For SN 1972e, however, the emission lines persisted for at least two years. During that time energy must have been supplied to the ejecta at a rate that decreased exponentially, just as the supernova's overall brightness did. What are the possible sources of that energy?



EVOLUTION OF SPECTRUM OF TYPE II SUPERNOVA is shown for SN 1970g in M101. Numbers to left are number of days past star's maximum brightness. Peak labeled [*O I*] shows the development of an emission line of un-ionized oxygen some months after the explosion.



CHANGE IN SUPERNOVA'S RADIUS can be measured and is shown in billions of kilometers. Two months after the explosion of this star (SN 1969l in the galaxy NGC 1058) it had attained a size much larger than that of the solar system. At this point outermost layers of the star become transparent and visible surface of star appears to shrink. Such measurements can be combined with other information to determine distance from our galaxy to supernova's.

One continuing source might be the radioactivity of some isotope or group of isotopes with a half-life of between 50 and 70 days. In the 1950's Baade, Geoffrey Burbidge, E. Margaret Burbidge, Fred Hoyle, Robert F. Christy and William A. Fowler suggested that the isotope was californium 254. The radioactivity hypothesis, with the radioactive isotope or isotopes being something other than californium, has been revived many times. The intense heat, pressure and bombardment by neutrons in the center of the supernova may well produce heavy radioactive elements and could create the extra iron that may be present in the envelope of a Type I supernova.

A second continuing source of energy that might keep the emission lines glowing is a pulsar. It is known, for example, that the Crab Nebula in the constellation Taurus is a remnant of the supernova explosion observed by Chinese astronomers in A.D. 1054. It is also known that in the center of the nebula is a pulsar, a fast-spinning neutron star that is emitting large amounts of energy in the X-ray, light and radio regions of the spectrum. Since the spinning neutron star is emitting so much energy, it is slowing down, and the rate at which it is slowing down indicates that the amount of energy emitted corresponds to the amount emitted by the entire Crab Nebula. It seems reasonable to expect that in the first few years after the explosion the energy lost from the pulsar could have provided the power needed for the observed emission lines.

No pulsars younger than the one in the Crab Nebula have yet been found. A spinning neutron star at the center of a supernova might, however, be concealed for a considerable length of time by the ejecta. If the debris surrounding the pulsar takes a while to blow away, the absence of rapid pulsations from the remnants of extragalactic supernovas may not be strong evidence against the formation of pulsars in such events.

So far I have been comparing observations of supernovas in other galaxies with theoretical models of supernovas,

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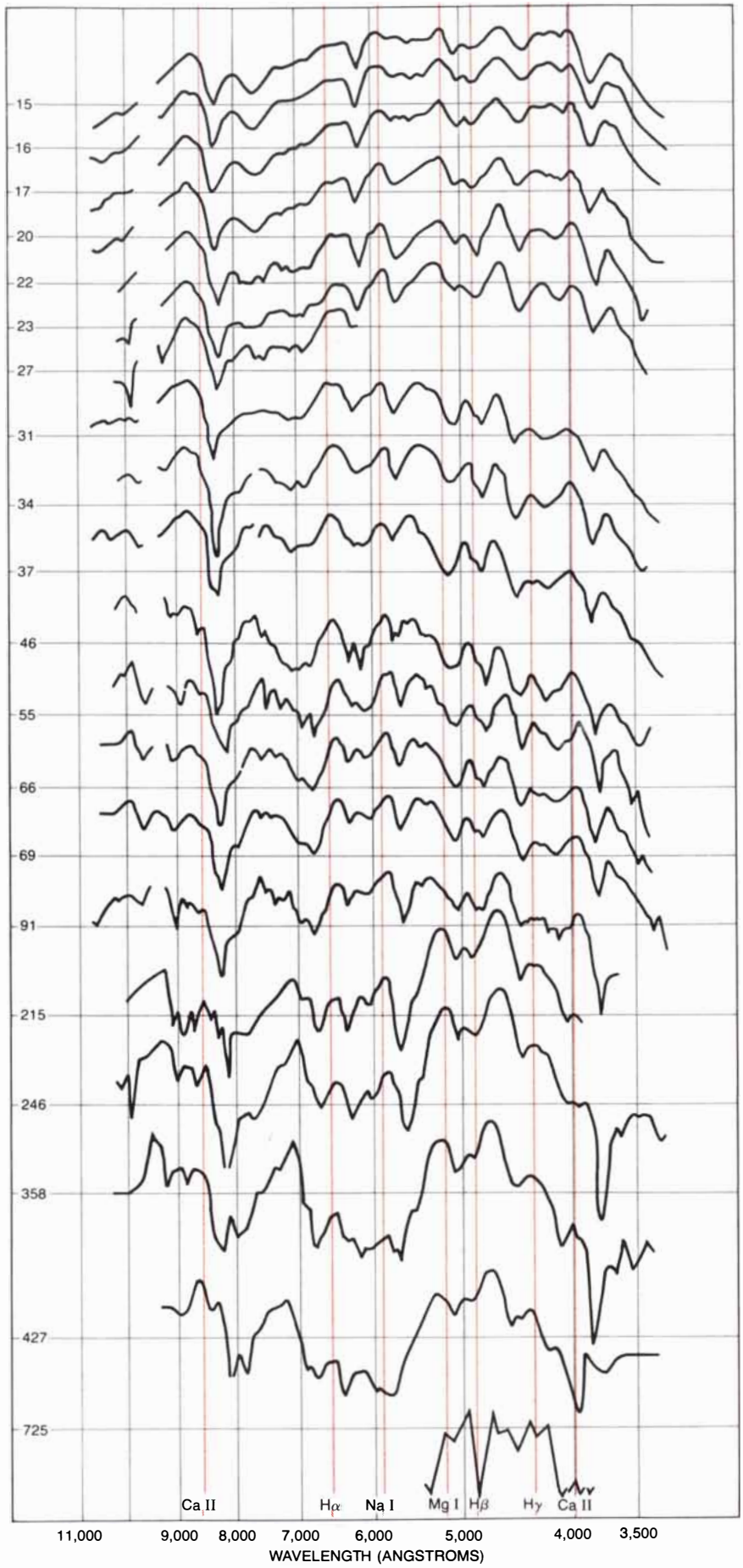
without regard to the question of why a star should explode catastrophically at all. A number of theorists have attempted to devise stellar models that describe not only the explosion but also the life history of the star up to that point.

In general the fate of a star depends on its mass. When a star is first coming into existence, the gas from which it is forming contracts and heats up, converting its gravitational energy into thermal energy. Eventually the temperature at the center of the gas gets high enough to fuse hydrogen nuclei by thermonuclear reactions. At that point the star settles down to a long stable period of burning hydrogen. After a time, however, the hydrogen fuel in the core of the star is exhausted. The core contracts further under the influence of its own gravity while hydrogen continues to be burned in a shell around it. Meanwhile the outer layers of the star expand and the star becomes a red giant.

For stars less massive than a few times the mass of the sun that is almost the whole story. When the hydrogen in the shell around the original core is exhausted, the thermonuclear reactions within the star cease. The star does not have enough mass for it to continue to collapse and heat up further. The gravitational forces are completely balanced by the electrostatic forces between the electrons in the cold, dense core, and the star remains stable. The outer layers of the red giant rather quietly expand away from the star, forming a planetary nebula such as the Ring Nebula in Lyra, and the star continues for billions of years as a feebly radiating white dwarf.

Much more massive stars are able to continue collapsing. Their core heats up until thermonuclear reactions can resume, this time fusing helium nuclei to produce carbon. When the helium too is exhausted, the core collapses further and carbon nuclei fuse to produce still heavier elements.

The models predict that two alternative kinds of catastrophe might befall such massive stars and give rise to supernovas of Type II. In the first case the ignition of carbon may lead to instabilities within the core that blow up the star. That could happen because the rate at which energy is generated in thermonuclear reactions is extremely sensitive to temperature. Under some conditions



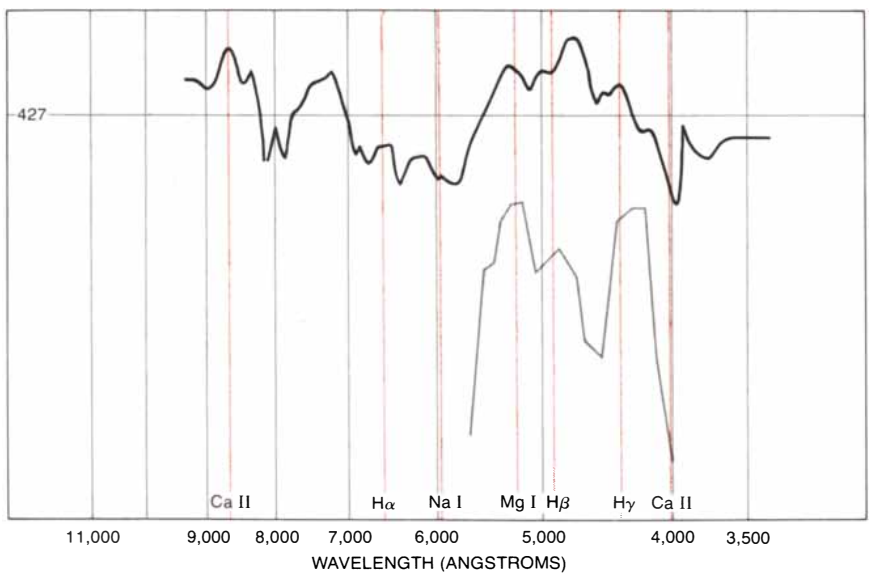
EVOLUTION of Type I supernova is shown for SN 1972e over a period of nearly two years. Late in the star's development the spectrum is dominated by four strong unidentified emission lines between the wavelengths of 4,000 and 6,000 angstroms. The emission lines mean that energy is somehow still being supplied to the gas surrounding the supernova long after the explosion. The energy may be coming from radioactivity or from a pulsar.

the ignition of carbon might increase the temperature in the core and thus increase the rate at which the carbon is burned. The higher rate of burning raises the temperature still further, which again increases the rate of burning. If no other mechanism interferes, the process quickly runs away, burning all the carbon in the star in a very short time. A catastrophic process of this type in the center of a red giant might give rise to just the kind of supernovas that are observed. One trouble with this model, however, is that it predicts the entire star will be destroyed and no stellar remnant of any kind will be left.

In the second case the star might go beyond the ignition of carbon without disaster. Such a star would have an extremely hot core that would produce copious amounts of neutrinos. Since neutrinos have no mass or electric charge and interact only weakly with other matter, they could escape from the star entirely, carrying with them much of its energy. As the core loses energy in this way it contracts and heats up still more. Here again the rate at which neutrinos are produced increases with temperature. As they carry away more energy the temperature would continue to go up until finally the core would go into a headlong plunge toward total collapse. Near the end of the collapse it might emit a final burst of high-energy neutrinos. As the burst passed through the star's outer envelope it could transfer enough momentum from the core to the envelope to blow off the exterior layers and give rise to a supernova. Meanwhile the only force available to halt the complete collapse of the core is the "strong" force that acts between atomic nuclei. If that force can brake the collapse, the core would become a neutron star, an extremely dense but stable object.

This alternative would lead to the natural formation of a neutron star in the death of every massive star. The best calculations made so far of what happens in the collapsing core of a star, however, show that a neutron star is not formed. Instead the core collapses all the way down to a black hole, one of those bizarre postulated objects from which not even light can escape. Nature pays no heed, however, to the problems of theorists. It is clear that a neutron star does exist in the center of the Crab Nebula, and it is also clear that the nebula is the remnant of a supernova explosion, so that at least some supernovas produce neutron stars.

The train of events leading to a supernova of Type I is more mysterious than that leading to one of Type II, since a Type I supernova is expected to be the explosion of a star about as massive as the sun. Since such a star can comfortably settle down to being a white dwarf, something unusual must happen for it to explode as a supernova. It is generally hypothesized that a star that becomes a Type I supernova is a member of a binary, or double-star, system. Under certain conditions when such a star becomes a white dwarf, large amounts of material could flow into it from its companion. The new material could increase the mass of the white dwarf past the critical limit of 1.44 solar masses, at which point the star would begin to collapse. The process by which the star would become a supernova is not clear, but it is fairly certain that the collapsing white dwarf could release the amount of energy observed in a Type I supernova. Whether or not this theoretical picture resembles what actually happens in an observed supernova of Type I is not yet known.



THREE OF THE FOUR EMISSION LINES in the spectrum of SN 1972e (*shown on preceding page*) may be due to emission from ionized atoms of iron, according to the identification of the author and J. Beverley Oke. Top curve is next to last spectral curve for SN 1972e shown on preceding page. Bottom curve is the calculated spectrum of iron formed from a blend of 216 emission lines. Emission line still unaccounted for, however, is the strongest of the four lines.

The combination of the fact that heavy elements are manufactured in the core of a presupernova star and the fact that a supernova explodes so cataclysmically has led to the hypothesis that supernovas might be responsible for enriching the gas between the stars with heavy elements. The interstellar gas is primarily hydrogen and helium, but it has significant trace amounts of elements heavier than hydrogen and helium. Moreover, in the heat and violence of a supernova explosion an immense flux of neutrons might be generated that could build iron into the heaviest elements. If the heavier elements in the interstellar gas originated in this way, it is possible that supernovas are responsible for the heavier elements in the sun, the earth and the earth's living organisms.

An important piece of direct evidence in favor of this hypothesis comes from meteorites. Certain meteorites are believed to be chunks of matter left over from the time when the sun and the planets were forming out of a cloud of dust and gas. Detailed examination of the composition of such meteorites shows that they contain some of the decay products of relatively short-lived radioactive nuclei. For example, iodine 129 has a half-life of 17 million years; its decay product, the inert gas xenon 128, is found locked up inside the meteorites. The observation implies that the radioactive iodine must have been present when the meteorite was formed. This implication in turn implies that the material that was destined to become the solar system included a fresh supply of radioactive iodine. Perhaps a supernova somewhere in the vicinity of the nascent solar system created the radioactive iodine, blasted it into the interstellar gas and possibly even triggered the formation of the solar system. Whether or not this entire chain of reasoning is correct, the isotopes in meteorites are strong evidence that heavy elements were being manufactured in the era during which the solar system was forming.

Further observational evidence for the synthesis of heavy elements in supernova explosions rests on two cases: the Crab Nebula and a supernova remnant in Cassiopeia known as Cassiopeia A. In the Crab Nebula the abundance of helium with respect to hydrogen appears to be higher than it is in other regions of the galaxy. In Cassiopeia A oxygen, sulfur and argon appear to be unusually abundant with respect to hydrogen. It may be that nuclear processes in the supernova

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that gave rise to each of these remnants account for the unusual abundance of the heavier elements in them.

Supernovas may also account for cosmic rays. The earth is steadily bombarded by energetic particles from outside the solar system, some of them with energies higher than those of the particles produced by the most powerful man-made accelerators. If the energies of the cosmic-ray particles are multiplied by the density of the particles, the total energy turns out to be comparable to that of all the starlight in the galaxy combined. What could be the source of these energetic particles?

Supernovas have been one of the possible answers to that question since Zwicky made the suggestion in 1933. Stirling A. Colgate of the New Mexico Institute of Mining and Technology and his collaborators have pointed out that as the powerful shock wave from the explosion of a supernova's core speeds through the outer layers of the star the density of the matter it encounters progressively diminishes. They suggest that when the shock wave gets to layers of relatively low density, its tremendous energy is transferred to such a small amount of mass that individual nuclei are accelerated to velocities approaching the speed of light.

Another way in which supernovas could create cosmic rays has been put forward by John Scott and Chevalier on the basis of their investigations of the supernova remnant Cassiopeia A, the brightest object in the radio sky. The radio emission of the object comes from particles traveling near the speed of light in a magnetic field. Visual observations of Cassiopeia A show that small knots of gas are traveling through it at a few thousand kilometers per second, a characteristic velocity for supernova ejecta. Scott and Chevalier posit that the knots stir up the magnetic fields within the supernova remnant, which in turn accelerate the particles to the energies characteristic of cosmic rays.

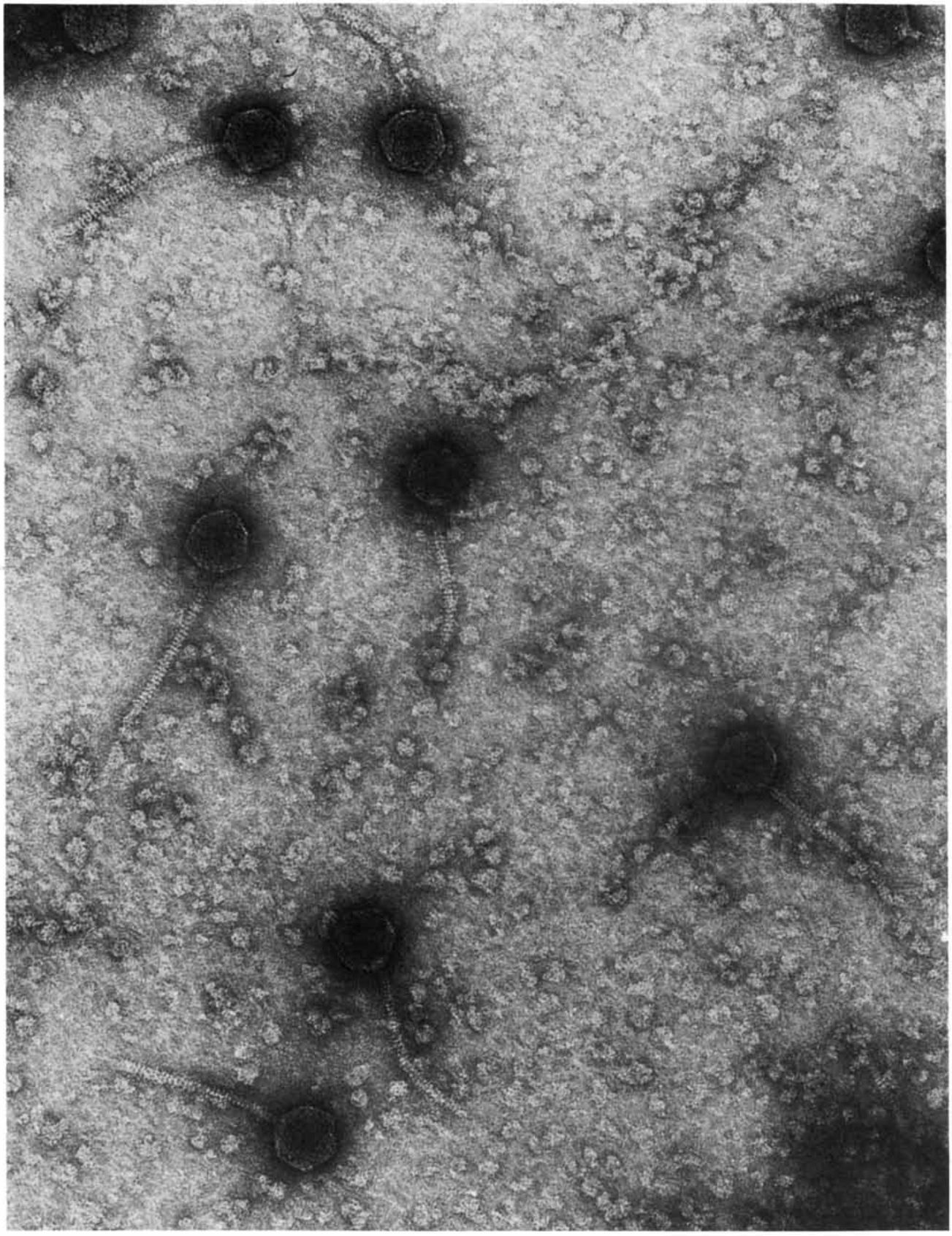
Supernovas are also in a unique position to contribute to establishing the distance scale of the universe. The technique of spectrophotometry provides both the temperature of the supernova's surface and the amount of energy received from the exploding star on the earth. The amount of energy emitted from the surface of a star of a given temperature depends only on the area of the surface, which is proportional to the square of the radius. And the energy received on the earth depends only on the total amount of energy emitted by the star and the inverse of the square of the distance between the earth and the star. Therefore the star's temperature and the energy received on the earth give the ratio of the radius of the star to the distance of the star. Doppler-shift measurements show how fast the star is ex-

panding. Thus if one obtains two sets of data from the supernova separated by a few weeks, one knows the distance by which the radius of the star has increased. Knowing this distance and the ratio between it and the distance to the earth, one can readily calculate the distance of the star.

Although there are many uncertainties in the detailed application of this technique, which was first suggested by Searle, it has the unique property of being a measure of extragalactic distances that is completely independent of the standard distance scale, which is based on distance determinations made in our own galaxy. John Kwan and I found that for two supernovas, SN 1969l in NGC 1058 and SN 1970g in M101, the distances derived by the technique agreed rather well with the extragalactic distance scale derived in the traditional way by Allan Sandage and Gustav A. Tammann of the Hale Observatories. Although we need more test cases and better models of supernovas, the method holds high promise as an extragalactic distance indicator.

Counting extragalactic supernovas provides an estimate of the rate at which they explode in our own galaxy. A rate of one every 50 years or so seems reasonable. Tycho Brahe observed a supernova in 1572, and Johannes Kepler observed another in 1604. A detailed study by Sidney van den Bergh of the David Dunlap Observatory of the University of Toronto of the motions of the knots in Cassiopeia A indicates that it exploded about 1667, although it was not mentioned by Isaac Newton or by anyone else at the time. Presumably the supernova that created the remnant Cassiopeia A was dimmer than most and was somewhat obscured by interstellar dust. There is no evidence that any supernova has exploded in our galaxy during the intervening 300 years.

What will the next supernova be like? Will it be like the Crab Nebula supernova, visible in the daytime and, as the Chinese reported, "as big as a mat"? Or will it be like the Cassiopeia A supernova, unseen and unimpressive? A quantitative guess has been made by van den Bergh, who has calculated the number of stars in the galaxy at different distances from the earth and the expected extinction of their light by interstellar dust. His results indicate that although the next supernova may be very bright, it is just as likely to be an inconspicuous new star in the middle of the dusty Milky Way, where it may not be noticed at all. It may be that by the time the next supernova explodes in our galaxy we shall first detect it not by its light but by the huge burst of neutrinos it sends out, by the gamma rays emitted by the heavy radioactive elements it synthesizes or by the pulse of gravitational waves generated by the collapse of its core.



BACTERIAL VIRUSES, or phages, of the strain designated lambda are magnified 200,000 diameters in this electron micrograph made by William C. Earnshaw and Philip A. Youdarian of the Massachusetts Institute of Technology. Each virus particle has an icosahedral head containing a molecule of infectious viral DNA, and a flexible hollow tail with which the phage attaches itself to the outer membrane of its bacterial-cell host and injects its DNA into the interior of the cell. Negative staining with uranyl acetate clearly reveals the subunits that make up the virus's protein shell. The phage-lambda particles shown here were extracted from an infected strain of the colon bacillus *Escherichia coli,* together with a large number of bacterial ribosomes (*lightly stained particles scattered over background*).

How Viruses Insert Their DNA into the DNA of the Host Cell

Some viruses are able to coexist peaceably with their host cell for long periods, incorporating their genes into the host chromosome. The details of the insertion process are now fairly well understood

by Allan M. Campbell

The imagery of medicine often seems to portray viruses as aggressive organisms bent on human destruction. In actuality their role in disease is merely a by-product of their parasitic existence. Unable to reproduce by themselves, viruses must invade living cells and redirect some of the cellular machinery to the production of new virus particles. In the process many of the host cells are destroyed, leaving the tissue of which they are a part damaged and giving rise to disease.

Although virus production and cell destruction are the most dramatic outcomes of virus infection, they are by no means the only outcomes possible. Like other parasites, many viruses find it advantageous to persist innocuously within their host cell for an indefinite period, actively multiplying only when the host weakens or stops growing. The existence of such latent viruses was first suspected in the 1920's, but it was not until the early 1950's that André Lwoff and his colleagues at the Pasteur Institute established unequivocally that a latent virus, or "provirus," can be transmitted from one cell generation to the next without external reinfection. Working with bacteriophages, the viruses that infect bacteria, they showed that the provirus exists in a "lysogenic" state. The term lysogenic refers to the fact that the provirus can come out of the dormant state and give rise to mature virus particles that lyse, or dissolve, the bacterial cells. Among the agents that can induce the provirus to resume its former mode of multiplication are ultraviolet radiation, X rays and carcinogenic chemical compounds. In the intervening 20 years the further study of bacteriophages has revealed much about the mechanism of lysogeny.

A typical bacteriophage consists of a single linear molecule of nucleic acid enclosed in a protein coat. Resembling a minute hypodermic syringe, the phage attaches itself to a bacterial cell and injects its strand of DNA into the interior. Once inside the cell, the viral DNA may begin directing the manufacture of new virus particles or become a provirus by incorporating itself into the DNA of the bacterial cell's long, threadlike chromosome.

What then switches the provirus from the lysogenic state to the active production of virus particles? A mechanism was put forward by François Jacob and Jacques Monod of the Pasteur Institute in 1961 and later demonstrated by Mark Ptashne of Harvard University. In the provirus only a few genes are expressed, and the product of one of them is a "repressor" protein that combines with the viral DNA and prevents the expression of the other viral genes, particularly those responsible for the independent replication of the viral chromosome. Inducing agents such as X rays alter the metabolism of the bacterium in such a way that a substance is produced that inactivates the repressor. If all the repressor molecules in a given lysogenic bacterium are simultaneously inactivated, the viral genes are sequentially expressed. Proteins needed for the replication of the viral DNA are made first, followed by the head and tail proteins of the virus particle, which spontaneously assemble inside the bacterium. Unit segments of viral DNA are then packaged into the phage heads. Finally, some 60 minutes after the cell was exposed to the inducing agent, the cell bursts, releasing about 100 virus particles that are capable of infecting other cells.

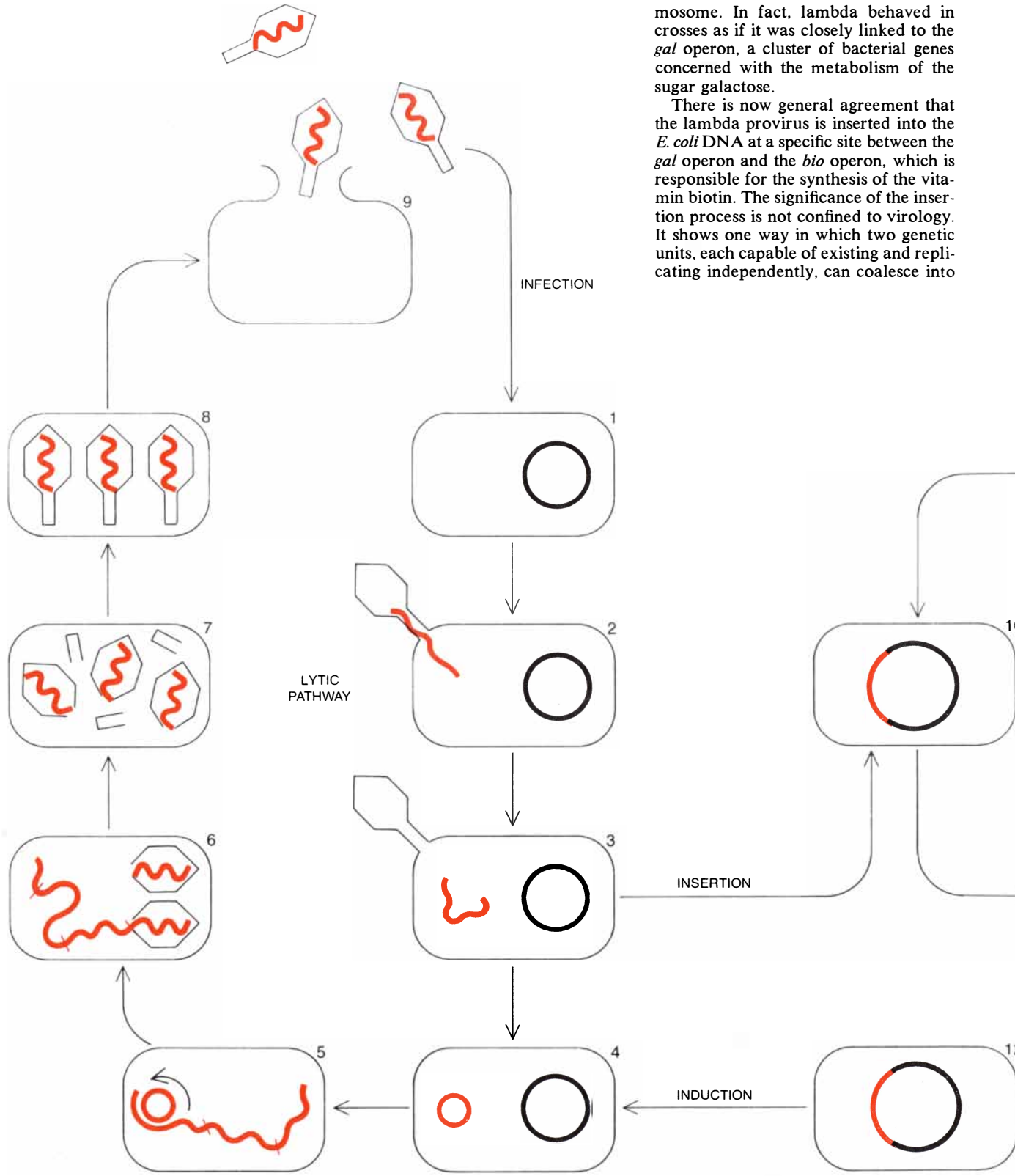
When a single lysogenic bacterium multiplies to form a colony, every cell of that colony is potentially capable of manufacturing virus particles and can express that potentiality when its repressor is destroyed. The viral genes have therefore been added to the bacterial genes in such a way that both sets of genetic information are inherited by the cell's descendants. In order for this to happen the viral chromosome must replicate like any normal cellular component, and it must be partitioned at cell division so that each daughter cell receives at least one copy of it.

Such a result can be achieved in at least three possible ways. One is for the viral chromosome to insert itself into the host chromosome, after which it can be passively replicated and distributed at cell division as part of the host DNA. Another way is for the viral chromosome to establish itself independently; it replicates and is distributed like the host chromosome but is separate from it. A third way is for the viral chromosome to replicate separately from the host chromosome and in multiple copies. In that case the viral chromosome might not be distributed regularly when the bacterial cell divides, but if the number of copies is large enough, the chance of a daughter cell's receiving no copies whatever is small. If we survey all known viruses, we find that the first two mechanisms exist in nature, and the third is observed in certain mutant viruses produced in the laboratory. One property all three mechanisms have in common is that once the virus has become established as a hereditary component of the cell, there is nothing particularly novel in its mode of inheritance from then on.

Bacteriophage lambda, which was discovered by Esther M. Lederberg of Stanford University as a provirus carried by the K12 strain of the colon bacillus *Escherichia coli,* is the best-understood genetically of the bacteriophages and remains one of the favorite experimental organisms of molecular biologists. Soon after Lwoff's demonstration of heritable lysogeny several investigators were able to achieve genetic crosses between strains of *E. coli* that were lysogenic for phage lambda and strains that were nonlysogenic for it. They got the surprising result that the characteristic of being lysogenic or nonlysogenic was distributed among the progeny of the cross exactly as one would expect if the trait were being determined by a gene at a specific location on the bacterial chro-

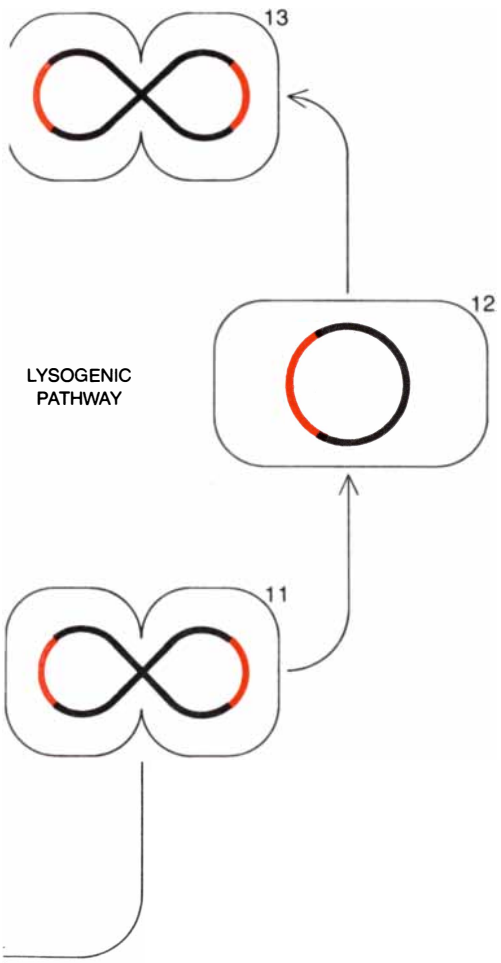
mosome. In fact, lambda behaved in crosses as if it was closely linked to the *gal* operon, a cluster of bacterial genes concerned with the metabolism of the sugar galactose.

There is now general agreement that the lambda provirus is inserted into the *E. coli* DNA at a specific site between the *gal* operon and the *bio* operon, which is responsible for the synthesis of the vitamin biotin. The significance of the insertion process is not confined to virology. It shows one way in which two genetic units, each capable of existing and replicating independently, can coalesce into



LIFE CYCLE OF PHAGE LAMBDA shows that lysis (dissolution) and death of the infected bacterial cell are not inevitable. After a molecule of viral DNA is injected into a healthy *E. coli* cell (*2*) the host may take either of two paths. In the productive, or lytic, pathway the viral DNA forms a circle (*3 and 4*) and replicates by the "rolling circle" process to give rise to a long "sausage string" of DNA containing multiple copies of the viral genes (*5*). Next the viral genes direct the synthesis and assembly of the head and tail proteins of the virus particles and the packaging of unit DNA segments into the heads (*6 and 7*). Heads and tails then assemble spontaneously inside bacterium, giving rise to mature phage particles (*8*). Finally, some 60 minutes after infection, the host cell bursts, releasing about 100 progeny virus particles that can then infect other *E. coli* cells (*9 and 1*). Alternatively, depending on the conditions of infection, the phage-lambda DNA can live quietly within the host, establishing itself as a semipermanent part of the bacterial chromosome (*10*). It is then replicated and segregated at cell division (*11 and 12*) and passed on to succeeding cell generations for an indefinite period. The latent virus,

a larger unit. Phage lambda is only one of a number of elements for which insertion is known or suspected. Most of these elements are viruses or the small pieces of bacterial DNA called plasmids, some of which can transfer resistance to antibiotics and other properties from one bacterial cell to another. In addition there are the "insertion sequences" of bacteria and the "transposable elements" of maize, which are known only for their ability to move occasionally from one chromosomal location to another and may well have no independent existence.



or "provirus," still retains the potential to grow lytically, however. Bacteria harboring a provirus are called lysogenic, meaning that they carry a property that can lead to viral multiplication and the fatal lysis of the host cell. Exposure of lysogenic bacterium to ultraviolet radiation, X rays or chemicals such as nitrogen mustard and organic peroxides can induce the provirus to return to lytic pathway.

Although the widespread occurrence of genetic elements that can insert themselves into preexisting chromosomes is incontestable, there is a considerable divergence of opinion about their importance in the normal life of the host or in evolution. One extreme viewpoint is that these elements are basically foreign to the cells that harbor them; they are invaders like viruses that have somehow got into cells and chromosomes and do not really belong there. The alternative view is that much of the DNA of present-day chromosomes is derived from elements that were originally foreign but that through a series of small evolutionary steps gradually became naturalized citizens of the intracellular community. A somewhat intermediate position is that the mobility of these elements plays some essential role in the normal development of multicellular organisms from the fertilized egg into the adult.

Studies of the mechanism by which new genetic elements are added to existing chromosomes cannot provide any direct information about the origin or function of such elements. The studies are, however, relevant in one respect. If it turned out that the DNA of the added elements was hooked onto the rest of the chromosome in some unusual way, by connections that were not normal features of chromosome structure, then a clear distinction between foreign DNA and indigenous DNA would be implied. It therefore seemed particularly important to firmly establish whether or not the foreign DNA of some prototypical examples such as the lambda provirus is directly inserted into the linear sequence of genes on the host cell's chromosome.

The concept of genes' being arranged in a linear sequence, and the experimental basis of that concept, have a long history. In 1913 A. H. Sturtevant of Columbia University crossed fruit flies differing from each other by several genetic traits and analyzed the frequencies of progeny exhibiting new combinations of the parental traits. He concluded that the determinants for these traits (all of which happened to be on the same chromosome) distributed themselves as though they were on some one-dimensional structure, with new combinations arising from the redistribution of connected segments of that structure. It became possible to extend this kind of formal linkage analysis in the 1950's, when Seymour Benzer of Purdue University, working with small segments of phage chromosome, proved that the linkage maps of mutational sites within genes were also one-dimensional. These purely genetic studies were followed by cytological and biochemical work showing that the one-dimensionality of linkage maps was associated with the linear arrangement of the genes along the chromosome and ultimately with the linear sequence of nucleotides along the double helix of DNA.

The question of whether all the linear DNA segments in a chromosome are joined end to end in one continuous double helix is still not completely settled, but the evidence is increasingly strong that they are. The uncertainty surrounding the question through the mid-1960's was such, however, that many bacterial geneticists found nothing particularly bizarre in the notion that the provirus might lie alongside the host chromosome rather than being inserted into it.

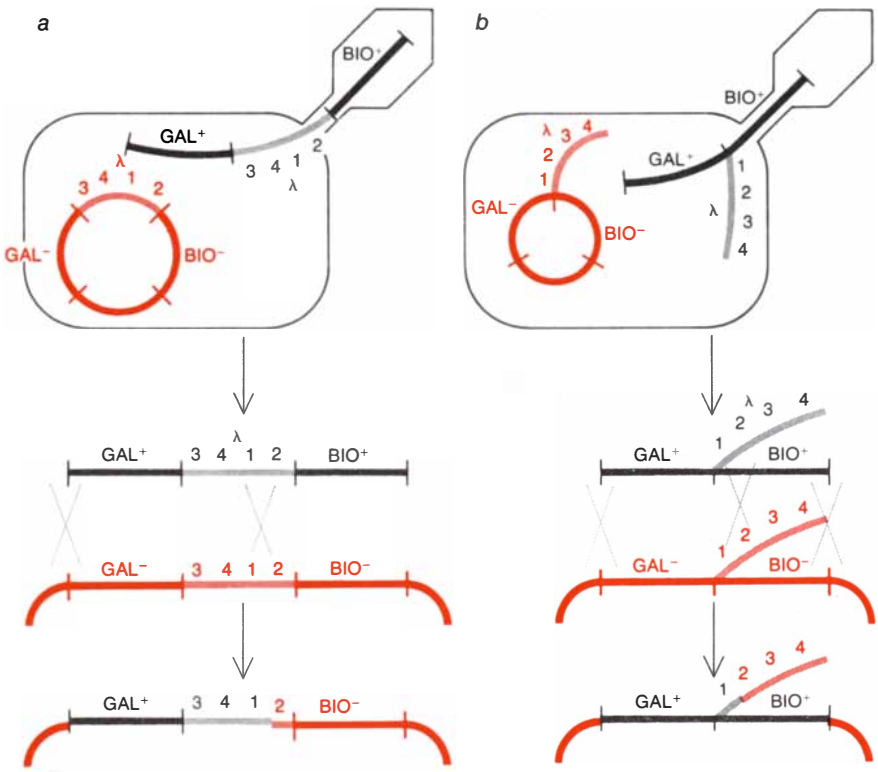
One way to investigate the question is to cross two lines of lysogenic bacteria, in which both the host genes and the viral genes are marked with mutations. In such bacterial crosses pieces of DNA from the donor cells are introduced into the recipient cells, where they pair with corresponding segments of the recipient cells' DNA and, in some fraction of those cells, replace them. Progeny in which a specific gene has been replaced can be recognized and selected for because they express a genetic trait characteristic of the donor, such as the ability to metabolize galactose. The recognition of the replacement of specific genes in the provirus has been made easier in recent years by the isolation of conditionally lethal mutant viruses, which fail to multiply in some condition under the control of the experimenter but which grow normally when that condition is changed. For example, temperature-sensitive mutants survive and multiply at one temperature (25 degrees Celsius) but not at another (42 degrees C.).

Such experiments throw some light on the provirus's mode of attachment. If, for example, the provirus is not linearly inserted into the host chromosome but instead projects from it sideways, one would expect that an exchange of genetic material occurring along the viral segment would not redistribute the genes lying on the main axis of the host chromosome. The fact is that redistribution of the host genes does occur, suggesting that insertion is indeed linear.

A second and more informative method of determining the topology of the lysogenic chromosome is deletion mapping, in which mutants marked by chromosomal deletions are crossed with strains that have other genetic markers. A deletion mutation involves the permanent loss from the chromosome of a string of neighboring nucleotides, numbering from one to many thousands. Since each deletion eliminates a continuous segment of chromosome, the order of the genes along the chromosome can be deduced by piecing together the information provided by the characteristics of the various deletion mutants observed. Deletion mapping provides a strict "betweenness" criterion for locating genes with respect to one another. The condition that every observed dele-

INSERTED ELEMENT	APPROXIMATE LENGTH IN NUCLEOTIDES	INSERTED INTO	SPECIAL PROPERTIES
BACTERIOPHAGE LAMBDA	50,000	*E. COLI* CHROMOSOME	SPECIFIC SITES ON VIRUS AND HOST CHROMOSOMES
BACTERIOPHAGE MU-1	37,000	*E. COLI* CHROMOSOME	SPECIFIC SITE ON VIRUS, ANY SITE ON HOST CHROMOSOME
BACTERIAL SEX FACTOR *F*	100,000	*E. COLI* CHROMOSOME	MANY SITES ON HOST CHROMOSOME
DRUG-RESISTANCE PLASMID	20,000	BACTERIAL FACTOR RESEMBLING *F*	TRANSMITS RESISTANCE TO ANTIBIOTICS BETWEEN BACTERIAL STRAINS
TUMOR VIRUS SV-40	5,000	HUMAN CHROMOSOME	DERIVED ORIGINALLY FROM MONKEY CELLS
TRANSPOSABLE ELEMENTS	(UNKNOWN)	MAIZE CHROMOSOMES	NO DETECTABLE EXTRA-CHROMOSOMAL PHASE
INSERTION SEQUENCE IS2	1,400	*E. COLI* CHROMOSOME	

ADDED GENETIC ELEMENTS, small pieces of DNA that can exist as part of the main chromosome or independently, have been observed in bacterial, maize and human cells. Some are viruses; others are not. When they are inserted, they introduce into the cell instructions governing additional biochemical reactions that may be superimposed on the cell's metabolism.



TYPES OF GENETIC EXCHANGE, or recombination, observed between two lysogenic *E. coli* chromosomes containing different genetic markers shed light on the mode of attachment of the phage-lambda genes. In the experiment depicted here a fragment of DNA from a bacterial cell capable of metabolizing galactose and synthesizing biotin (*gal*$^+$*bio*$^+$) and containing a lambda provirus with mutations in genes *1, 2, 3* and *4* is introduced by means of an infective phage coat into a recipient bacterium that is unable to utilize galactose or synthesize biotin because of genetic mutations (*gal*$^-$*bio*$^-$) and that harbors a nonmutant provirus. Type of recombination that might occur if the viral genes were linearly inserted into each chromosome is shown in *a*. The mechanism of insertion proposed by the author requires the permutation of the order of genes along the viral chromosome, so that a genetic exchange between viral genes *1* and *2* would serve to recombine the flanking bacterial markers *gal* and *bio*. The resulting recombinant bacterium would be capable of utilizing galactose but incapable of synthesizing biotin, a prediction that agrees with observed results. For comparison, *b* indicates the expectation for one kind of nonlinear topology, in which the provirus joins to the chromosome as a branch.

tion should be representable as a linear segment is a highly restrictive one; a segment represented by two deletion markers must necessarily include all points that lie between them. For example, if the provirus is inserted between two identified host genes, then every deletion removing both of those genes must remove the provirus as well. This turns out to be the case in experiments, and it is again consistent with the model that the provirus is continuous with the host DNA.

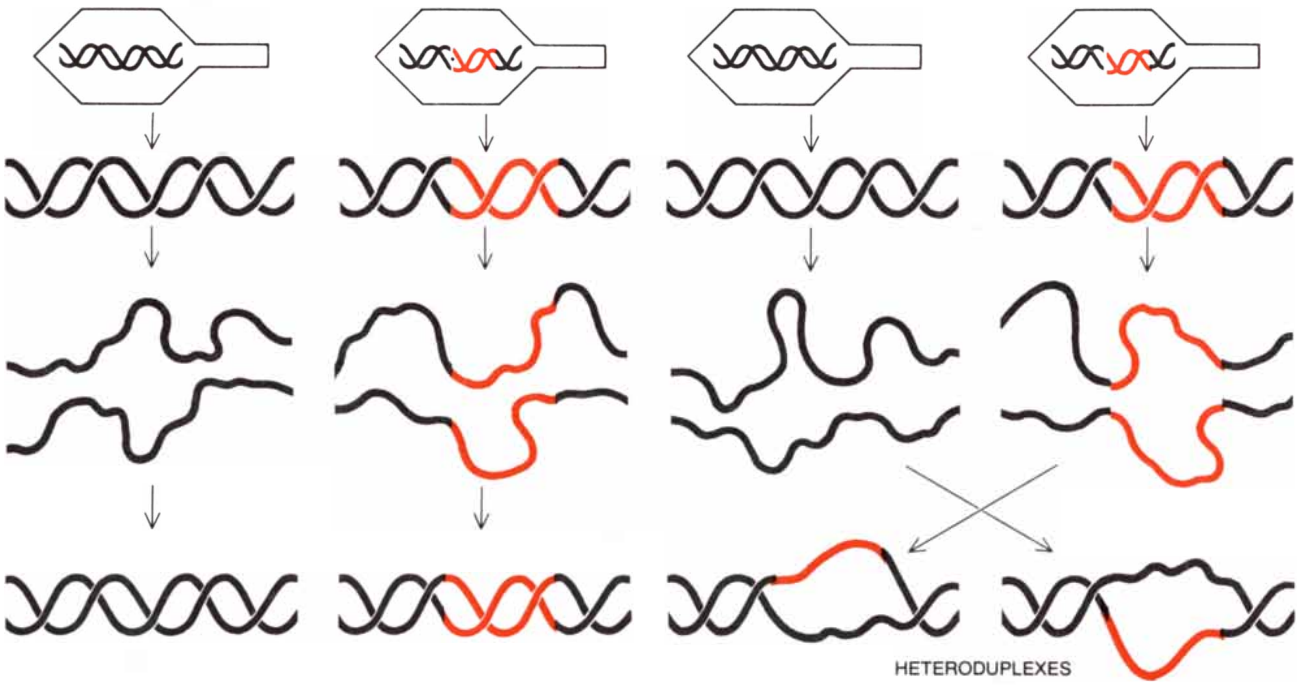
Until the beginning of the 1970's genetic analysis of the type I have been describing provided the only precise information on the relation between the provirus and the chromosome; no direct physical information was available on the relevant nucleotide sequences within the DNA of the provirus. In principle the simplest approach would be to use direct methods of determining the sequence of nucleotides along the DNA chains of the virus and the lysogenic chromosome. Although such sequencing methods are improving rapidly, the identification of all 50,000 nucleotides in the lambda provirus would be a time-consuming and costly task. For many purposes adequate information can be obtained by exploiting the fact that single DNA chains with complementary nucleotide sequences can find each other and form double helixes in the test tube. Electron micrographs of DNA molecules formed this way, notably in the laboratory of Norman R. Davidson at the California Institute of Technology and that of Waclaw T. Szybalski of the University of Wisconsin, have demonstrated that the structures inferred from genetic results have a physical reality.

For these experiments double-strand DNA molecules extracted from virus particles are dissociated into single chains by heating. If the solution is then cooled slowly, double helixes of the complementary chains will re-form. When single-strand DNA's from two viruses with some nucleotide sequences in common (such as phage lambda and a deletion mutant of it) are mixed before the cooling step, new helixes can form not only between complementary chains from one virus but also between complementary chains from both viruses; the latter kind of chain is known as a heteroduplex. The nucleotides in the complementary segments of these hybrid chains pair up and form double helixes but the noncomplementary sequences do not, leaving single-strand loops that can be seen in electron micrographs.

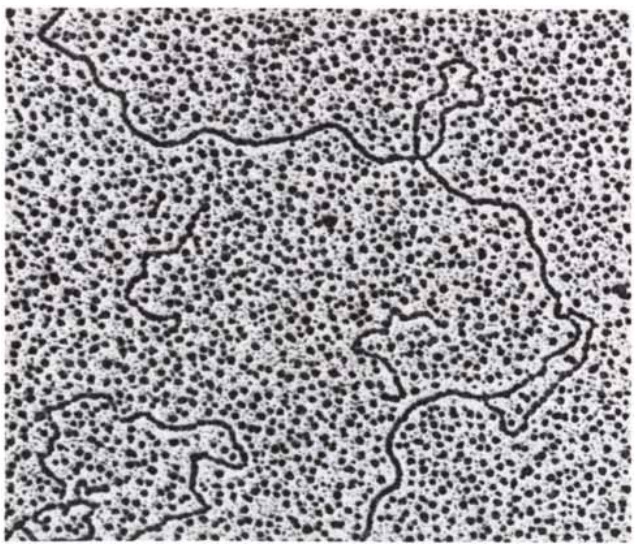
By some ingenious manipulations Davidson and his colleagues Phillip A. Sharp and Ming-Ta Hsu were able to examine heteroduplexes between viral

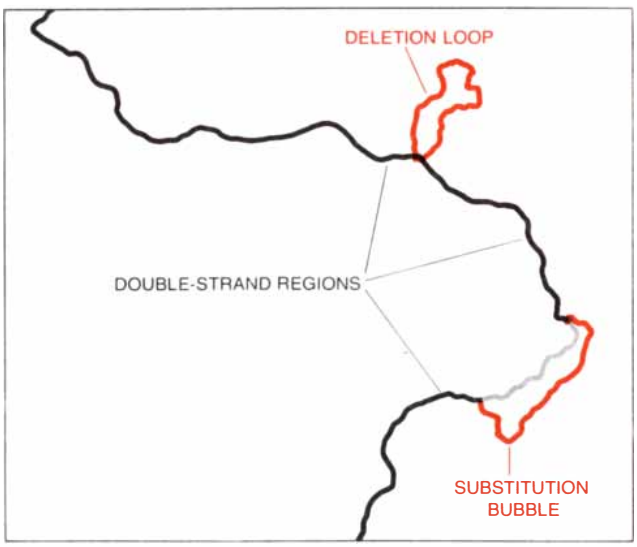
DNA and the DNA of an inserted provirus. Although the most straightforward approach would be to make heteroduplexes from one DNA chain of phage lambda and the complementary chain of a chromosome from a lysogenic bacterium, that experiment is not yet feasible because of the difficulties in handling a DNA molecule the size of the bacterial chromosome. The same end was achieved by letting the phage-lambda DNA insert itself not into the entire bacterial chromosome but into a smaller DNA molecule: a derivative of the bacterial sex factor that had picked up from the bacterial chromosome the specific DNA segment into which lambda inserts. Strands of the sex factor with the lambda provirus inserted into them could be readily isolated intact and used to form heteroduplexes with DNA extracted from virus particles.

The combined results of genetic and physical studies make us quite confident



HYBRID DNA MOLECULES artificially formed in the test tube can be used to map viral genes physically. When the DNA double helix is heated, it unwinds, giving rise to two single-strand chains. If single chains having complementary and noncomplementary regions are mixed together at this stage and slowly cooled, some "duplexes" will form between the chains. When these heteroduplexes are viewed in the electron microscope, the two DNA chains will be double helixes where they have the same sequence of nucleotides and unpaired where they differ in sequence. With this method one can precisely map position of a given marker mutation along the DNA molecule.

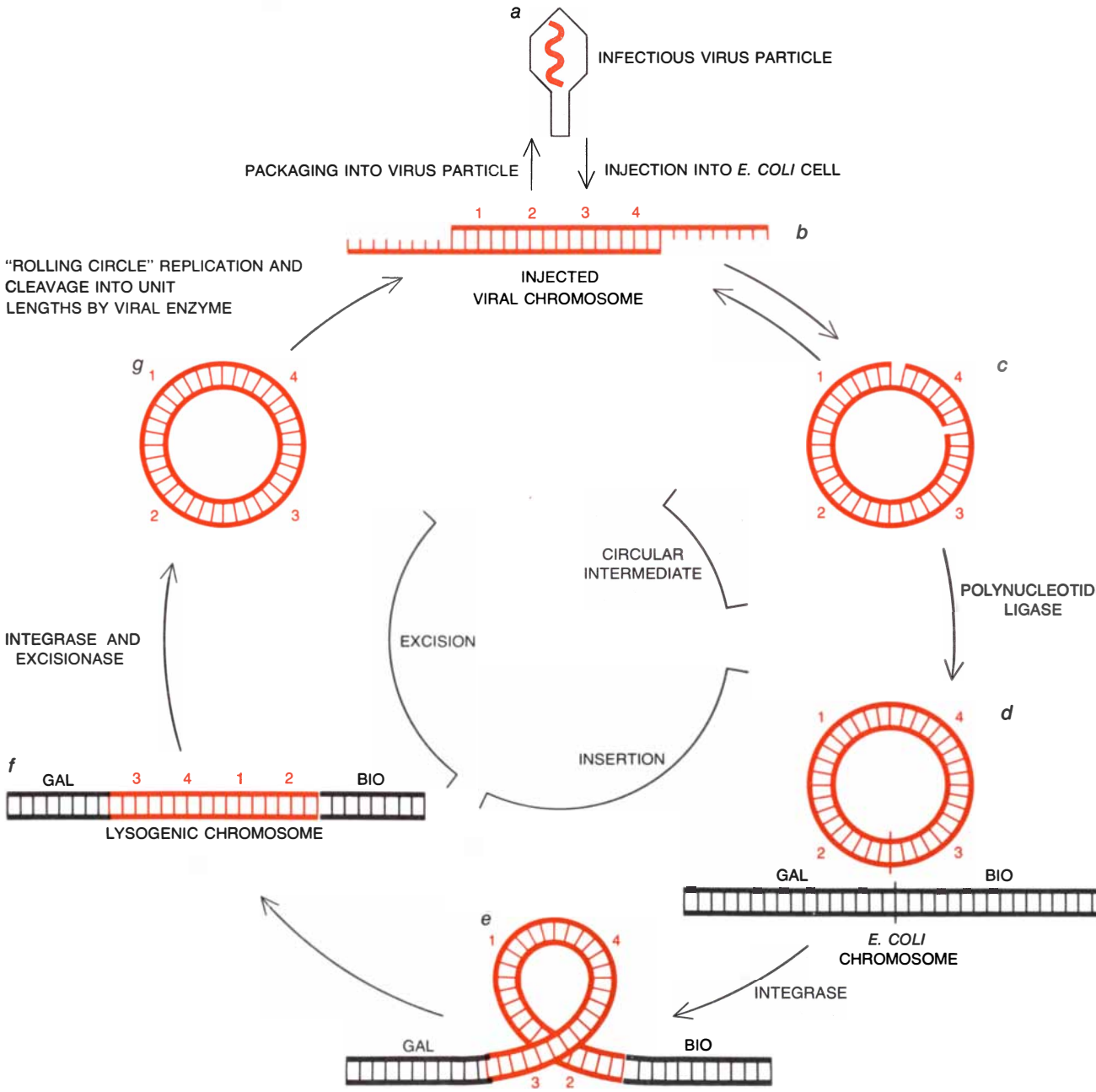




HETERODUPLEX between a strand of normal lambda DNA and a second strand incorporating two mutations is clearly visible in this electron micrograph made by Elizabeth A. Raleigh of M.I.T. (Only a small segment of the long viral DNA molecule is shown.) The loop of single-strand DNA at top right results from a deletion mutation that removed an entire segment of DNA from one strand. The "collapsed bubble" of single-strand DNA results from the substitution of several nucleotides in one strand by different ones, making that region of the two strands noncomplementary and hence unable to pair. The remaining portions of molecule shown here are double-helical.

that we now know the structure of the lysogenic chromosome. The steps by which this structure is formed and dissociated into its component parts are the subject of current research. During the life cycle of phage lambda, DNA must be cut and rejoined at the ends of the viral chromosome and at the ends of the provirus. The lambda DNA injected into the bacterial cell is in linear form, but before it is inserted into the bacterial chromosome its ends are joined so that it makes a circle. During insertion the circle is opened at a different point. As a result, although the provirus and virus chromosomes are both linear structures, the order of the genes along the two is not identical.

How the ends of the viral DNA are joined to form a circle is known, thanks largely to the work of A. D. Kaiser and



INSERTION AND EXCISION of the phage-lambda genes into the *E. coli* chromosome require the action of both bacterial and viral enzymes. As the DNA of phage lambda is packaged in the viral particle (*a*) it is linear and double-helical, except for complementary unpaired segments 12 nucleotides long at the ends of the two nucleotide chains (*b*). In solution this linear form comes to equilibrium with a circular form that has staggered "nicks" 12 nucleotides apart in the two complementary chains (*c*). When viral DNA is injected into the bacterial cell in the course of infection, the two nicks in the open circle are sealed by the bacterial enzyme polynucleotide ligase, so that both chains of the circle are now closed throughout their length (*d*). This circular intermediate then interacts with a particular segment of the *E. coli* chromosome (between the *gal* and *bio* genes). Viral and bacterial chromosomes break and rejoin at unique sites on each partner, so that viral DNA is spliced into the host DNA, a reaction catalyzed by the viral enzyme integrase (*e*). (Note that the gene order in the provirus is *3, 4, 1, 2*, a cyclic permutation of the viral gene order *1, 2, 3, 4*.) The *E. coli* chromosome is now lysogenic for phage lambda (*f*). After several cell generations radiation or chemically active compounds may induce the provirus to enter the lytic state. When this happens, the lambda repressor, which has so far blocked the expression of most of the viral genes, is inactivated, allowing the synthesis of the viral enzyme excisionase. Together with integrase, excisionase catalyzes the excision of the provirus from the host chromosome, converting it back into the circular form with the original gene order (*g*). The circle of viral DNA replicates, producing multiple copies that are then cleaved by a specific viral enzyme to give rise to the linear form with "sticky" ends (*b*). Each linear DNA segment is then packaged in a virus coat (*a*). When the host cell ruptures, the liberated phages infect healthy cells and the lysogenic cycle begins anew.

his collaborators at Stanford. Lambda DNA is a double helix throughout most of its length, but one end of each polynucleotide chain extends for 12 nucleotides beyond the double helix. These two single-strand chains are complementary to each other and are called "sticky ends." In solution the linear DNA molecules can come to equilibrium with circular molecules formed by the pairing of the two ends. When lambda infects an *E. coli* cell, the open circle formed by the viral DNA is closed by the action of polynucleotide ligase, a bacterial enzyme that seals breaks in one chain of a double helix. This step requires no viral enzymes, and it is not specific to the nucleotide sequences involved. On the other hand, the insertion of viral DNA into the bacterial chromosome requires the recognition and cutting of highly specific nucleotide sequences in both the lambda and the *E. coli* DNA.

Little is known of the biochemistry of insertion, although its genetic control has been intensively explored. At the time I proposed the circular-molecule-intermediate model for the insertion of phage-lambda DNA in 1962, the only known mechanism for breaking or rejoining two DNA molecules at corresponding points was homologous recombination, which requires that the two molecules have similar or identical base sequences in the recombining region. The chemical steps by which homologous recombination takes place are still largely conjectural, but Alvin J. Clark of the University of California at Berkeley and others have isolated bacterial mutants that are unable to carry out this process. Under conditions where homologous recombination is blocked by such mutations, however, phage lambda can still insert its DNA with the normal frequency. Hence the insertion of viral DNA seems to be accomplished not by the same bacterial enzymes that are responsible for homologous recombination but by viral enzymes that cut and join DNA molecules at highly specific sites.

Direct evidence for the existence of such viral enzymes has been provided by the genetic studies of James F. Zissler of the University of Minnesota Medical School and the biochemical investigations of Howard A. Nash of the National Institute of Mental Health, which have shown that the enzyme product of a specific viral gene (dubbed integrase) is required for the insertion of viral DNA; mutant viruses lacking this enzyme are unable to enter the lysogenic state. Similar studies of the reverse process—the excision of viral DNA from the bacterial chromosome—by Gabriel Guarneros and Harrison Echols of the University of California at Berkeley and Susan Gottesman of the National Cancer Institute—have shown that excision

When I was a child, I spake as a child, I understood as a child, I thought as a child: But when I became a man, I put away childish things. —*I Corinthians*

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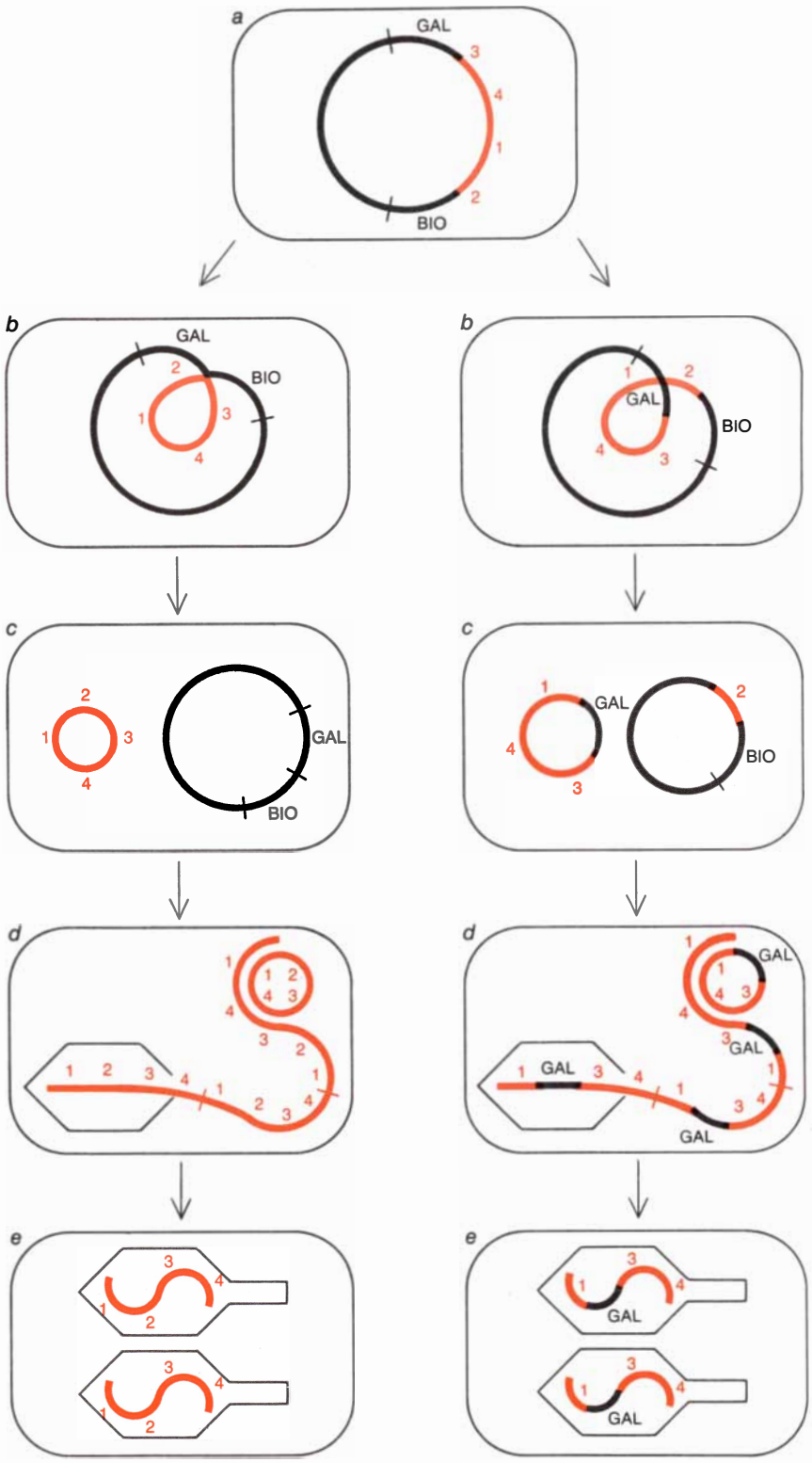
requires in addition to integrase the product of a second viral gene (called excisionase). The virus thus introduces into the host cell enzymatic machinery for cutting and joining the viral and host DNA at specific sites to bring about the insertion and excision of the provirus. As long as the transcription of the gene coding for excisionase is blocked by the lambda repressor the provirus will remain inserted. When repression is released, the excisionase gene will be expressed and there will be a reciprocal exchange within the lysogenic chromosome, re-creating a circular molecule of lambda DNA and a nonlysogenic bacterial chromosome.

Excision is generally precise: more than 99 percent of the virus particles manufactured by lysogenic cells are identical with the original infecting virus. This fact implies that the DNA breaks at exactly the same point when it comes out of the chromosome as it does when it goes in. About one excision in 100,000, however, is abnormal. Instead of breaking away cleanly the host DNA and the viral DNA break and rejoin to create a circular DNA molecule incorporating some viral DNA and some host DNA. If the size and physical characteristics of the molecule allow it to be recognized by the viral proteins as being suitable for replication and packaging as a virus, it can then give rise to infectious particles in which a segment of host DNA has replaced part of the viral DNA.

M. Laurance Morse of the University of Colorado Medical Center first discovered the existence of these "transducing" virus variants when he found that some of the phage-lambda particles liberated from lysogenic bacteria contained the *gal* genes of the host. When lambda and lambda-*gal* DNA's were hybridized in the test tube, the heteroduplexes showed that nucleotides at the two ends of the molecules were complementary to one another but that in the middle of the duplex there was an unpaired region where the picked-up segment of bacterial DNA (including the *gal* operon) was not complementary to the viral DNA.

The theory that transducing phages are produced by errors in the excision of the provirus from the host chromosome was supported by the observation that under normal circumstances lambda can incorporate only genes, such as *gal*, that are within a few thousand nucleotides of its insertion site. This distance is a small fraction (less than 1 percent) of the total length of the host chromosome. Recently K. Shimada and his co-workers at the National Institutes of Health have studied rare bacterial lines in which lambda DNA has inserted itself into a chromosomal site other than the normal one. From such abnormal strains virus variants carrying *gal* are



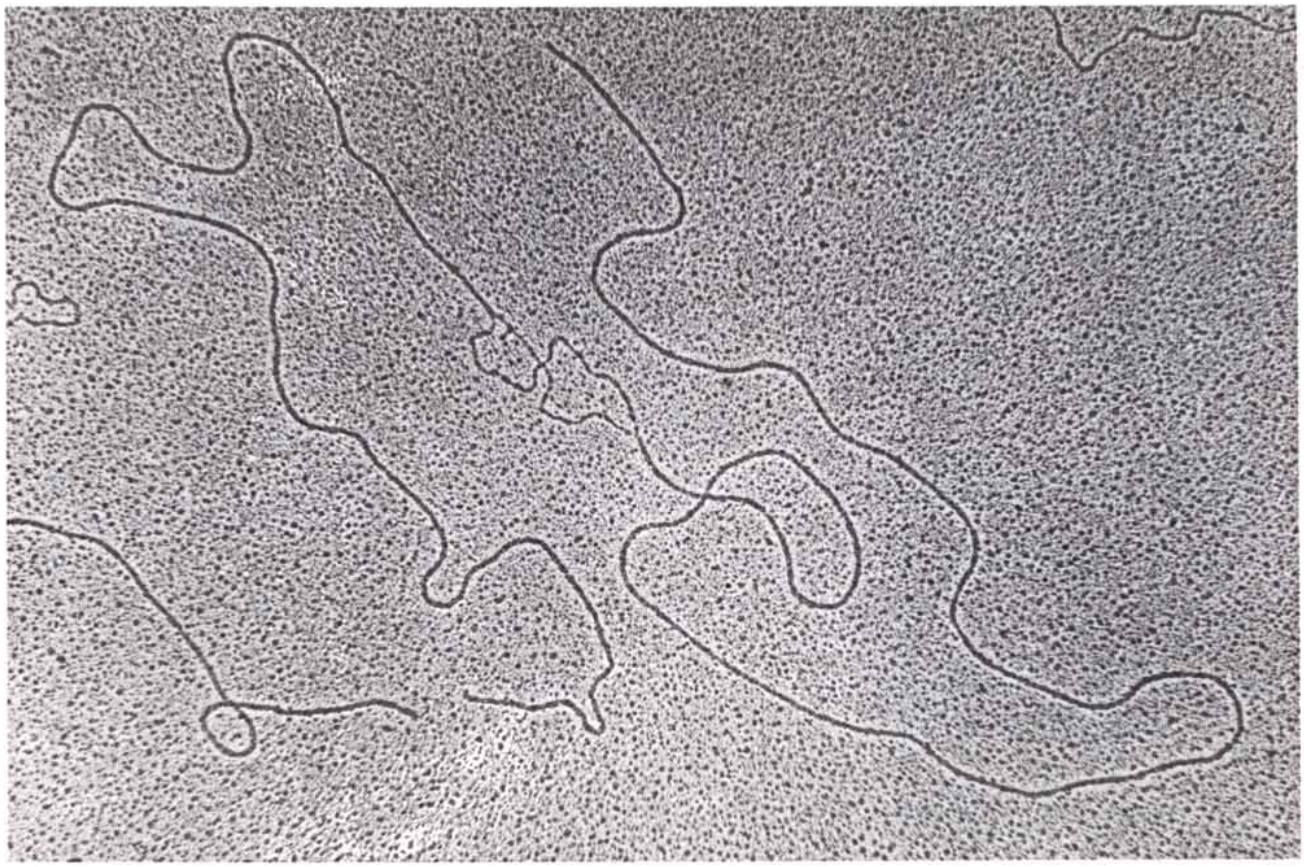
NOVEL VIRUS VARIANTS arise when certain proviruses turn into infectious viruses, killing the bacterium that harbors them and carrying away with them pieces of the DNA of the dead host. The "transduced" bacterial genes linked to the viral chromosome can subsequently replicate at the unrestricted viral pace. Transduction is believed to result from rare errors in the excision of the provirus from the host chromosome. Normal excision (*left panel*) takes place in the vast majority of cells. Viral DNA separates from the bacterial DNA (*b*) to give rise to a circular viral chromosome and a nonlysogenic bacterial chromosome (*c*). The viral chromosome replicates in several stages, ultimately as a rolling circle that generates a long sausage string of DNA in which the entire viral sequence is repeated many times (*d*). Unit DNA lengths are then packaged into infectious virus particles (*e*). In one cell out of 100,000 (*right panel*) abnormal excision generates a circular molecule including some host DNA. Infectious particles are thus formed in which a segment of bacterial DNA has replaced a segment of viral DNA.

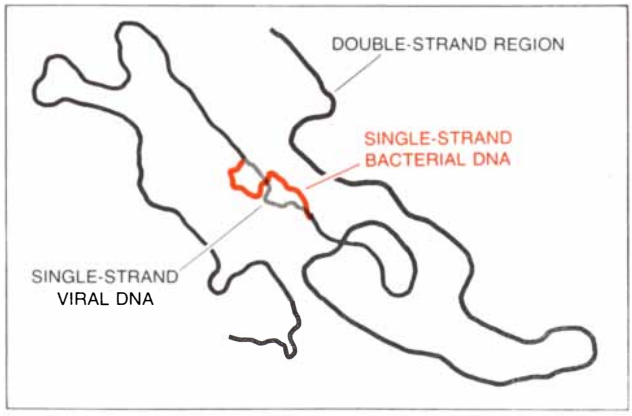
not obtained, but variants carrying genes close to the new attachment site are.

Why has the virus evolved such a complex and specific mechanism for getting its DNA into and out of chromosomes? The obvious answer is that the ability to do so at appropriate times plays an important role in the virus's survival. Little is known about the selective forces operating on viruses in nature, but one can imagine that it is to the virus's advantage for its DNA to be inserted soon after infection, for the DNA to remain stably inserted while the lysogenic bacterium is growing and for the DNA to be excised while the bacterial genes are repressed. Since insertion and excision have different enzymatic requirements, the virus can control both the direction and the extent of these activities by regulating integrase and excisionase.

The integrase reaction seen in phage lambda and similar viruses is the first case known where two DNA molecules are cut and rejoined at specific sites as part of the normal life cycle of an organism. Enzymatic cleavage and rejoining of DNA molecules in the test tube has become a common pastime of biochemists, but the bacterial restriction enzymes used for this purpose ordinarily function in DNA degradation rather than in genetic recombination. We do not yet know the actual nucleotide sequences recognized and acted on by integrase. The in vivo results require that the viral and bacterial sequences differ from each other, since the genetic requirements for insertion and excision are not the same.

The study of how the phage-lambda DNA inserts itself has provided some useful dividends, among them knowledge of the specific process of the breaking and joining of DNA molecules, which is becoming amenable to biochemical study and opens up new possibilities for the controlled translocation of DNA segments in other organisms. It has also given us the transducing virus variants, which have become workhorses of molecular biologists because they enable one to replicate specific segments of host DNA apart from the rest of the chromosome. In addition understanding





HETERODUPLEX made in the test tube between DNA from a transducing phage designated $\phi 80psu_3$ and DNA from the parental phage $\phi 80$ reveals the location of the inserted bacterial genes in the middle of the viral chromosome. The black lines on the map represent the double-helical regions where the nucleotide sequence on the DNA strands of both partners is complementary. The colored segment is thepieceof *E. coli* DNA 3,000 nucleotides long carried by the transducing phage; the gray segment is the piece of viral DNA 2,000 nucleotides long that is present in the normal phage $\phi 80$ but replaced by bacterial DNA in $\phi 80psu_3$. Viral and bacterial DNA sequences on opposing strands are not complementary and cannot pair, forming a substitution bubble. Total length of duplex molecule is about 43,000 nucleotides. Electron micrograph was made by Madeline C. Wu and Norman R. Davidson of California Institute of Technology.

the mode of viral DNA insertion has helped to define the ways in which inserted elements and chromosomes can interact functionally. The simplest examples come from instances of abnormal insertion within known genes, such as the insertion of lambda DNA into the *trpC* gene.

The work of Charles Yanofsky of Stanford and others has shown that the *trp* operon consists of five genes, each of which codes for a different enzyme catalyzing a specific step in the biosynthesis of the amino acid tryptophan; the genes are designated *trpA, trpB* and so on. This entire stretch of DNA is transcribed into messenger RNA as a unit starting from *trpE* and continuing to *trpA*. The messenger RNA then attaches itself to the ribosomes, the subcellular particles where the enzymes are synthesized. Near the beginning of the transcribed stretch is the specific nucleotide sequence known as an operator. In the presence of high concentrations of tryptophan a repressor protein binds to this sequence and prevents the transcription of the entire DNA segment. All five proteins are hence synthesized together when tryptophan is needed by the cell, but their synthesis is shut off by large amounts of the end product, a feedback control mechanism common to many operons.

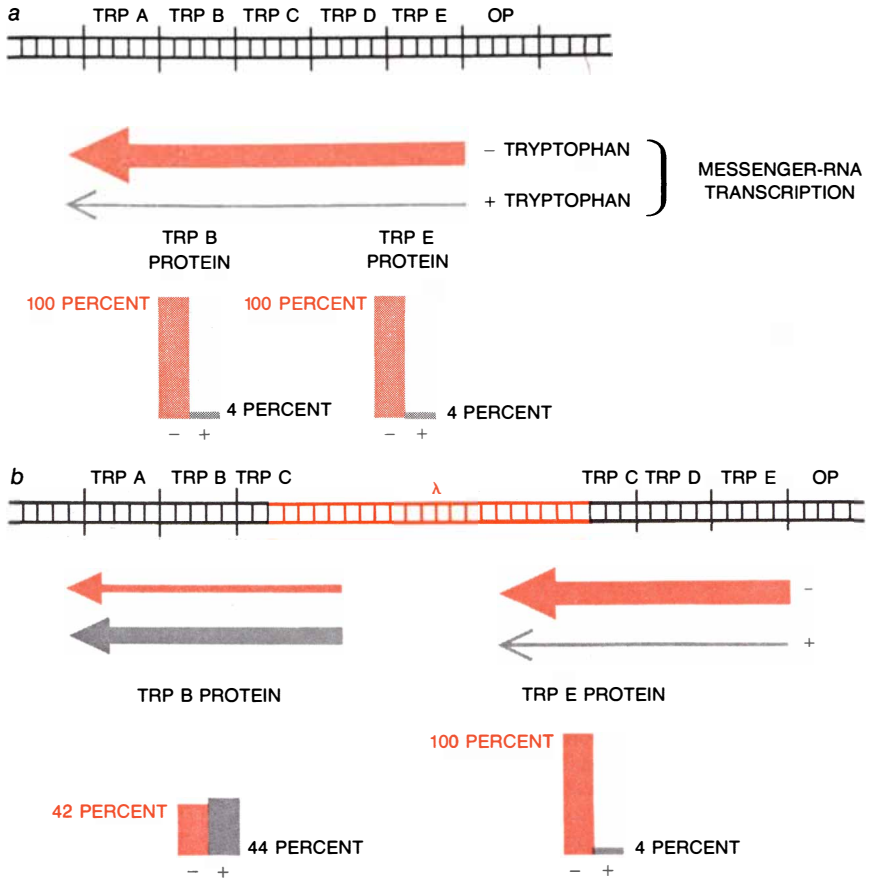
How does the insertion of phage-lambda DNA change things? First, since the lambda DNA goes into the middle of the *trpC* gene, the complete protein product of that gene can no longer be formed. A bacterium that carries the abnormally inserted provirus is thus unable to make tryptophan, since one of the enzymes in the biosynthetic pathway is not synthesized. It is possible to recover descendants of this lysogenic bacterium that have lost the provirus. In these bacteria the two halves of the *trpC* gene are rejoined, and active enzyme is again synthesized. None of the DNA of the *trpC* gene has been damaged or permanently lost; it simply cannot code for its normal product when it is cut in two.

Besides disrupting the *trpC* gene, the provirus interrupts the *trp* operon as a functional unit. The transcription of RNA ordinarily proceeds along DNA segments such as the *trp* cluster from a fixed starting point to some stop signal. The precise nature of transcriptional stop signals is not known, but somewhere within the lambda DNA there must be one or more of them. *TrpE* and *trpD* proteins are synthesized normally in these lysogenic bacteria, but the transcription from the *trpE* end never reaches the *trpA* or *trpB* genes.

The provirus can hence constitute a barrier to RNA transcription, although the junction points between provirus DNA and bacterial DNA are not themselves barriers. Whereas bacterial transcription that can be repressed by the product tryptophan does not reach the *trpA* or *trpB* genes, transcription arising from within the provirus does cross the junction between viral DNA and host DNA and produces a low level of tryptophan-independent expression of these genes. The viral transcript that extends across the junction includes only one known gene, the integrase gene of the provirus, which is expressed at a low rate even when the other viral genes are repressed. Thus insertion can not only break up units of transcription but also create new ones.

The transcription of RNA across boundaries in the abnormal lysogenic bacterium illustrates some of the consequences of the viral insertion of DNA both for the regulation of cell function and for evolution. If new regulatory units can be created by insertion, we can be sure that natural selection will then act on them to maximize their selective value to the cell. How extensively DNA of viral origin may have become incorporated into the regulatory systems of existing chromosomes is not known.

There is an old dichotomy between those virologists who view the virus basically as a foreign invader and those who view it more as a cellular component that escapes normal regulatory controls. The argument frequently concerns matters of definition rather than of substance, but it tends to recur at different levels of sophistication as knowledge increases. Lysogenic bacteria have long constituted a prime example for the cellular-component school. At present one can say this much: The conception of the provirus as a normal cellular constituent is at least not a superficial one. The provirus not only behaves like an integral part of the host chromosome; it really is an integral part of the host chromosome. In its manner of attachment there is nothing to distinguish the DNA of the virus from the DNA of the host.



ABNORMAL INSERTION of the phage-lambda chromosome into the *trp* operon (a group of bacterial genes coding for five enzymes in the biosynthetic pathway of the amino acid tryptophan) disrupts the operon's genetic control mechanism. In the normal operon (*a*) transcription of the *trp* genes into messenger RNA is regulated by the tryptophan concentration. When tryptophan levels in the cell are high, transcription is repressed, and when tryptophan levels are low, transcription and synthesis of the *trp* enzymes is high. If phage lambda inserts its DNA into the middle of the *trpC* gene (*b*), the operon as a transcriptional unit will be disrupted. Genes "upstream" from the viral DNA (*trpD* and *trpE*) will continue to be transcribed normally, but the transcript cannot pass through the viral DNA to the genes downstream from the provirus (*trpA* and *trpB*). These genes are expressed to some extent, however, because of transcription arising within the provirus that cannot be repressed by tryptophan. (Protein levels shown are for a mutant of lambda in which the rate of this transcription is abnormally high.)

Fission-Track Dating

The tracks left by the spontaneous fission of traces of uranium in many minerals are clues to the minerals' age. One of the main advantages of the technique is the broad span of time it covers

by J. D. Macdougall

The ability to measure the actual age of an ancient rock formation or a bone or an artifact of human culture is a comparatively new one. It stems from the fact that the radioactive isotopes of many common elements break down spontaneously at fixed rates. A familiar example is an isotope that is present in all living matter: carbon 14. Now a new radiometric method of absolute dating has begun to revolutionize chronological investigations in such diverse disciplines as cosmology, geology and archaeology. The new method measures the spontaneous fission of certain heavy elements, in particular the fission of the most abundant isotope of uranium, U-238. Given an appropriate sample for analysis, one can determine its absolute age over an enormous span of time: from as recently as a few decades ago to as far back as the time when the solar system was formed. The method is known as fission-track dating.

Fission tracks were discovered in the late 1950's by two workers at the British Atomic Energy Research Establishment at Harwell, E. C. H. Silk and R. S. Barnes. They had exposed samples of the crystalline mineral mica to ions produced by the fission of heavy elements. The ions were slowed and finally stopped by a series of interactions with the atoms in the crystal lattice of the mineral. As they did so they left thin linear tracks that were visible at extremely high magnification. In 1959 Silk and Barnes published electron micrographs of some of those tracks in the British physical journal *Philosophical Magazine,* thus establishing a new field of investigation.

It was soon demonstrated that almost any kind of energetic heavy ion would make tracks in a wide variety of solids. Then one group of investigators, Robert L. Fleischer, P. Buford Price and Robert M. Walker, who were then working at the General Electric Research and Development Center in Schenectady, pointed out that the spontaneous fission of the small amounts of uranium present as "impurities" in many different rocks would leave such tracks in crystals of the rock. Uranium 238 fissions at a characteristic rate, and when it does so, the two halves (more or less) of its nucleus violently recoil from each other and leave a characteristic track. Fleischer, Price and Walker suggested that studies of the number of tracks in the crystals of rocks would provide clues to the absolute age of the rocks. Today's application of this kind of track analysis to a multitude of questions in such unrelated fields as cosmic-ray physics and the study of human evolution has come about mainly through the pioneering work of these three men.

One of the first problems that had to be solved before fission-track dating could become a practical tool had to do with the fact that the tracks themselves were nearly invisible. In the mica specimens produced by Silk and Barnes the region affected by each impinging ion was only about 100 angstroms across—a fiftieth of a wavelength of light. At the high electron-microscope magnifications necessary to resolve such ultrafine features it would take many weeks to scan a single square centimeter of material in search of fission tracks. Then it was discovered that the region along the fission track where the crystal lattice is disrupted is less resistant to attack by a solvent than the undisrupted area of the lattice. For example, putting mica in an acid bath for an appropriate length of time dissolves the disrupted region along the track, creating a hole 100 or more times larger than the original track. This enlargement brings the tracks up to the micrometer range, where they are readily visible under the light microscope at magnifications of 500 to 1,000 diameters. Comparatively extensive surface areas can then be scanned quickly and accurately.

Precisely how are the fission tracks formed? The most satisfactory answer at present is one suggested more than a decade ago by Fleischer, Price and Walker and embodied in what they call the ion-explosion-spike model. According to this model, the fission fragment, moving at high speed and having a strong electric charge, ionizes the atoms along its path in the target material by stripping them of some of their electrons. If the target material is a conducting solid, as metals and certain minerals are, the stripped electrons are immediately replaced by free electrons, and the crystal lattice remains undamaged. If, on the other hand, the material is an insulating solid, as most rock-forming minerals are, the stripped electrons are not replaced, and the atoms are left with a net positive charge. Their mutual electrical repulsion pushes them apart, damaging the crystal. With one significant exception, the damage persists indefinitely.

An insulating solid can record a fission track even if it is not a crystal. Amorphous solids such as volcanic glasses, man-made glasses and plastics are also damaged by fission fragments. The process of track formation in these substances involves the breaking of chemical bonds rather than the disruption of a crystal lattice, but the net result is the same: a narrow region along the path of the fission fragment is made less resistant to chemical attack than the surrounding material.

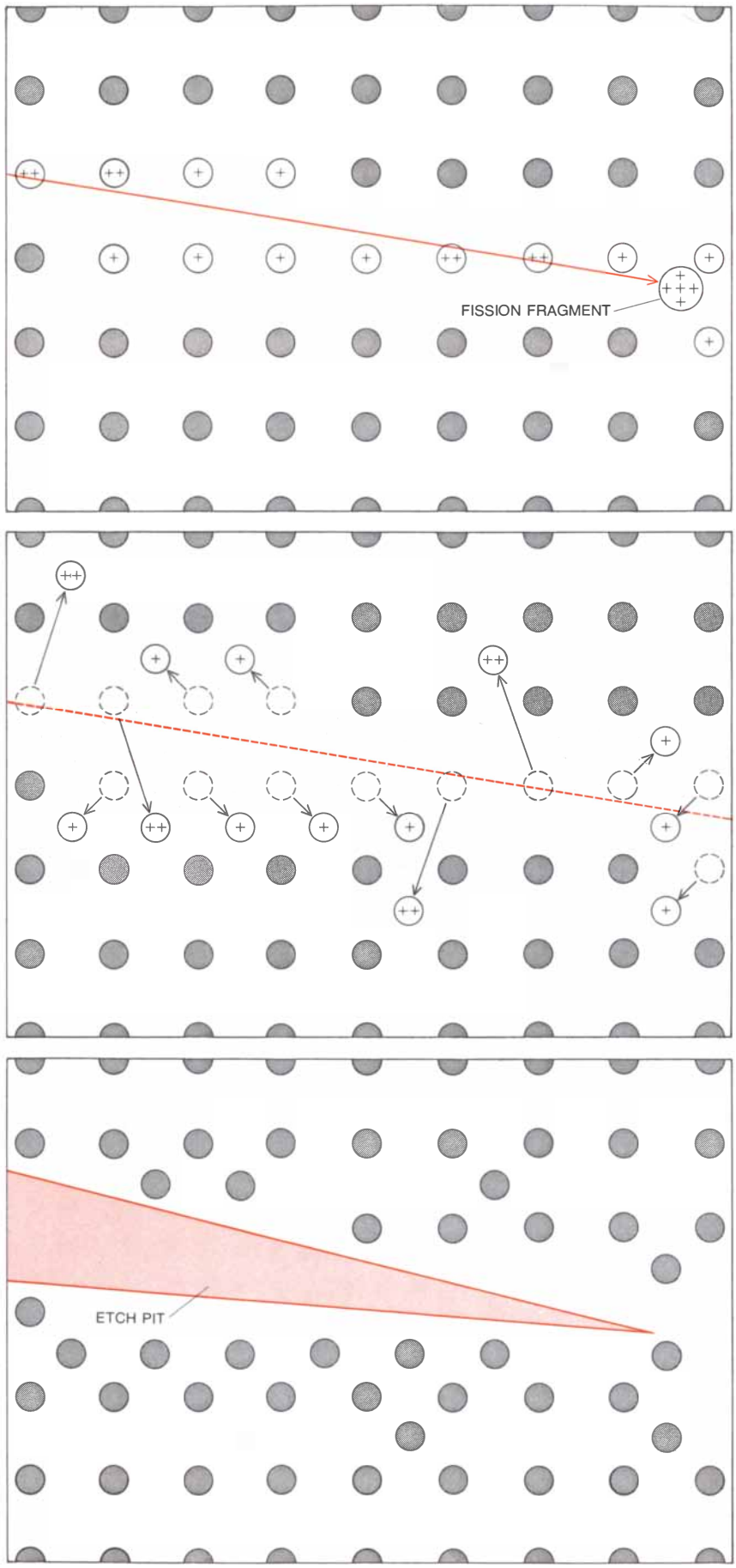
The basic method of dating by fission-track analysis is to count the number of tracks per unit area of the sample; in general the more tracks there are, the more fissions have occurred and the older the sample is. The method may seem somewhat different from other radiometric dating techniques, such as measuring the relative abundance of radioactive potassium and its argon daughter isotope, or of radioactive rubidium and its strontium daughter isotope. Actually the two kinds of dating are closely analogous; the only fundamental difference is that the one technique measures a product of decay and the other an effect of decay. Spontaneous fission is, however, a much rarer event than other kinds of radioactive decay. For example,

when one counts the tracks produced by uranium fission, their number may be in the hundreds, with each track recording the fission of one atom of uranium 238. Compare this with a high-sensitivity potassium-argon measurement, requiring about a ten-millionth of a cubic centimeter of argon 40. The argon sample represents the spontaneous decay not of a few hundred atoms but of roughly three trillion. The far smaller number of decays that provide the basis for fission-track analysis accounts for one of the great advantages of the method: very small samples can yield useful data. Under favorable circumstances the analysis of even a single microscopic crystal or a fragment of volcanic glass can determine the age of the specimen.

The average concentration of uranium in the rocks of the earth's crust is no greater than a few parts per million. Even at this low concentration the passing of a million years or so sees enough spontaneous fissions to leave a measurable number of fission tracks in some crystals. Furthermore, most of the crystalline rocks of the earth's crust are far more than a million years old, and so their crystals have accumulated a large number of tracks even though they contain little more than trace amounts of uranium.

Uranium 238 is the only significant producer of tracks in terrestrial rocks and in natural and man-made glasses. Other spontaneously fissioning elements exist, but they are rare and their rate of fission is slow. For example, it is estimated that the tracks produced by the spontaneous fission of another isotope of uranium, U-235, and thorium 232 combined represent less than .5 percent of the total number of tracks in the large majority of samples. As we shall see, however, the fact that even minute quantities of U-235 are present in glass-

FISSION TRACKS in a crystal of zircon appear in this light micrograph. The magnification is 3,100 diameters. Visibility of the tracks has been enhanced by an etching process that increases the diameter of each track from about 100 angstroms to a micrometer or more. Each track records the spontaneous fission of an atom of uranium 238; as much as 1,000 parts of U-238 per million is found in zircon.



es and mineral crystals is a great aid to the geochronologist.

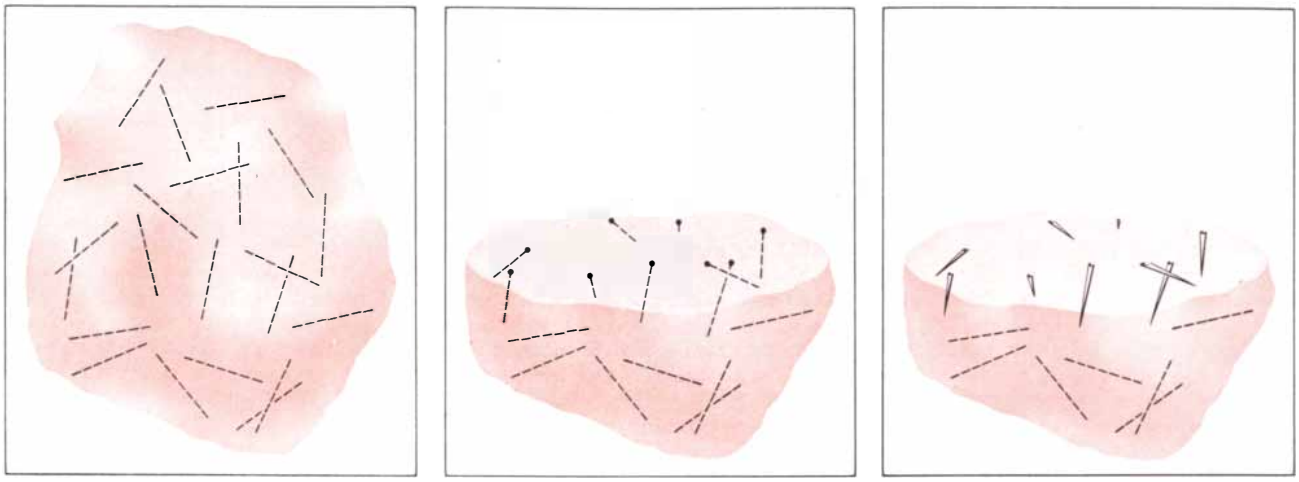
In the span of geologic time uranium 238 is transformed in two different ways. By far the commoner of the two is decay by the emission of an alpha particle. This emission transforms the uranium atom into an atom of thorium 234, a radioactive isotope that itself decays by the emission of an alpha particle. Alpha particles themselves are not, however, sufficiently massive or energetic to make tracks in common minerals.

About one out of every two million transformations in uranium 238 is by fission rather than by alpha decay. The process divides the uranium nucleus into two heavy and energetic fragments that differ only slightly in mass; at the same time several neutrons are emitted. The two heavy fragments fly apart in exactly opposite directions; the damage they do to the crystal lattice is thus in the form of a single straight track, approximately half of its length being created by each fragment. The overall length of the track varies, depending on the mineral involved; in general it is from 10 to 20 micrometers.

The usual procedure for studying tracks begins by embedding the specimen in a matrix such as an epoxy resin for convenience in handling. The exposed face of the crystal is then ground flat and carefully polished before the specimen is immersed in the etching bath. After etching, the crystal is observed under the microscope. The etching will of course reveal only the tracks that intersect the polished surface.

Since the rate of decay of uranium 238 by spontaneous fission is known, only two measurements are necessary to calculate the age of a specimen on the basis of the tracks visible after etching: a count of the number of tracks per square centimeter of surface and an assay of the U-238 content of the specimen. Since track densities are expressed

FORMATION OF TRACKS is shown schematically, following the model proposed by Robert L. Fleischer, P. Buford Price and Robert M. Walker. In the top diagram one of the two positively ionized fragments produced by the fission of a U-238 atom passes through an idealized crystal lattice; as it does so it strips electrons from the atoms along its path, thereby ionizing the atoms. Next (*middle*) the ionized atoms of the lattice are displaced, disrupting the structure of the lattice. When the crystal is exposed to a solvent (*bottom*), the disrupted portion of the lattice is more susceptible to etching than the undisrupted portion. Only insulating minerals record fission tracks; the free electrons in noninsulating solids restore the electrical neutrality of the momentarily ionized atoms before disruption of the lattice of the crystal can take place.



COUNT OF FISSION TRACKS requires preparation of specimen (*left*), containing tracks invisible under light-microscope magnifications, by grinding and polishing (*center*), thus exposing any tracks that intersect the plane of polishing. The specimen is next etched. The process causes pits to develop along each exposed track; these are large enough (*right*) to be easily seen under a light microscope.

in units of surface and uranium content in units of volume, however, a geometric ambiguity exists that has the potential for introducing considerable error. There is an ingenious method for determining the uranium content of a specimen that circumvents the problem. It capitalizes on the fact that a sample with uranium in it will contain not only uranium 238 but also a small but constant fraction of uranium 235.

The atoms of U-235 can be induced to fission by exposing the specimen to slow neutrons in a nuclear reactor. The exposure adds new fission tracks to the spontaneous ones. The density of the new tracks is proportional not only to the total amount of U-235 in the specimen but also to two factors under the control of the investigator: the probability of the induced fission reaction and the number of neutrons per unit area that have passed through the sample in the reactor. The proportion of the two uranium isotopes being constant in nature, the investigator can calculate the concentration of uranium in the specimen simply by comparing the number of spontaneous tracks with the number of induced ones. The two track counts can be made with a single sample or, if it is preferred, the sample can be divided. Moreover, exposing the sample to heat will erase fission tracks by annealing, so that the sample can be annealed after the count of spontaneous tracks has been made; the U-235 tracks later induced by neutron bombardment will then be the only ones present.

The older a specimen is, the less important it is that its uranium content be large; there will be enough fission tracks for a statistically reliable count. Conversely, when a fission-track date is sought from a specimen that is substantially less than a million years old, the date can be determined only if the uranium concentration is relatively high. As an example, the mineral zircon, which is a common constituent of many rocks, can contain some hundreds of parts per million of uranium. Zircon crystals with a uranium concentration of 100 parts per million can provide an absolute age for a rock sample only 3,000 years old. As a rule of thumb, if the uranium content of the sample of crystal or glass is one part per million, the investigator can measure an absolute age as young as 300,000 years. An order-of-magnitude change in either direction with respect to uranium content brings an inverselyproportionalorder-of-magnitude change in the youngest measurable age. Certain kinds of man-made glass contain as much as one part per 100 of uranium, and with them one can make an absolute-age determination up to as recently as 30 years ago. At the opposite extreme micas with a uranium concentration as low as a thousandth of a part per million can be used to measure absolute dates late in the Paleozoic era (300 million years ago).

All of this will make it seem that fission-track dating is remarkably precise, and for the most part it is. A few cautionary remarks should nonetheless be made. A fission-track age is calculated on the basis of four assumptions. The safest of the four, which is made in all methods of radiometric dating, is that the breakdown rate of the parent isotope (uranium 238 in the case of fission-track dating) has been constant with time. Both laboratory measurements and geological comparisons indicate that this assumption is sound. The other three assumptions are less certain.

One of them is that fission tracks are produced with 100 percent efficiency. Experiments indicate that this is so. When one encounters deviations from the expected number of tracks, they appear to be caused by problems affecting the techniques of track detection. Moreover, the possibility that error will result from this assumption is canceled when both spontaneous and induced fission tracks are examined. Even if the detection technique is only 10 percent efficient, as long as the efficiency applies equally to the detection of spontaneous and induced fission tracks the calculated age will remain correct.

The third assumption is that fission tracks are retained with 100 percent efficiency. Since there is always the possibility that tracks have been erased by natural or artificial annealing, this is an assumption that cannot always be justified. It can, however, be independently verified where other radiometric methods of dating are applicable. Such independent assessments show that most fission-track discrepancies fall consistently toward the young end of the scale. This is particularly evident when very old samples are examined. Except for slight random variations that usually fall within the range of experimental error, when the fission-track ages are shown to be wrong, they are almost never greater than the ages arrived at by alternative techniques of absolute dating. The reason is not hard to find: in most minerals used for fission-track dating the temperatures that suffice to erase tracks by annealing are well below the temperatures that begin to bias other methods of radiometric dating.

Moreover, in some instances fission-track ages that have been biased by partial annealing can be recognized and allowed for. As an example, if a particular mineral has been subjected to heat at some point in its history but the heat did not entirely anneal the tracks in it, measurements of the lengths of the tracks will show a bimodal distribution: one group consists of tracks shortened by partial annealing and another consists of tracks of normal length resulting

from spontaneous fissions after the episode of heating. With laboratory calibration experiments it is possible to correct the overall track-density figure for the effect of thermal shortening and arrive at a rebalanced figure for spontaneous-fission track density.

The fourth assumption presupposes that the concentration of uranium in any specimen has remained constant over the specimen's lifetime. This assumption is usually valid, but there can be exceptions. A combination of elevated temperatures and ground-water percolation can leach away a proportion of the uranium present in rock crystals. The mobility of the uranium is such that as one part of a rock formation is being impoverished another part can become abnormally enriched. Such changes can also take place at relatively low temperatures. Andrew J. W. Gleadow and John F. Lovering of the University of Melbourne have compared heavily weathered grains of apatite, a common mineral in rocks, with unweathered grains still embedded in the parent rock. The weathered grains contained approximately 25 percent less uranium than those in the parent rock and yielded anomalous age determinations.

The best way to indicate both the present usefulness and the future potential of fission-track dating is to cite some examples of its application. I shall mention only briefly that geologists have found fission-track dating particularly attractive when a chronological framework must be established in order to solve a particular field problem. The reason is that the system is simple, and when a large number of determinations are required, the cost per sample is low. All three major rock classes—sedimentary, metamorphic and igneous—are amenable to fission-track analysis. In igneous rocks the uranium-rich minerals that are commonly used include two I have mentioned, zircon and apatite. A third such mineral is sphene, a calcium-titanium silicate. Several varieties of mica have also been used successfully to date both igneous and metamorphic rocks.

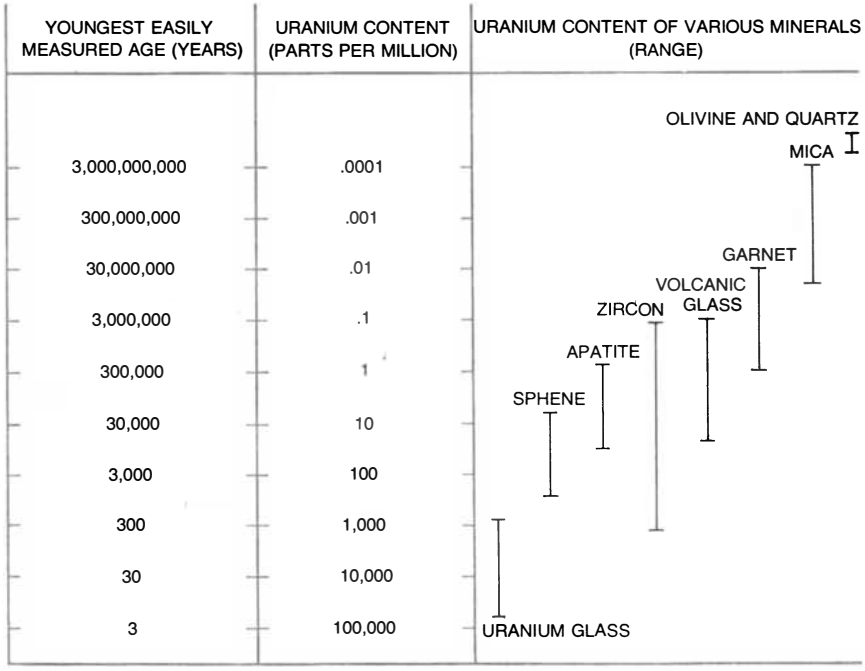
Applications of fission-track dating in the field of prehistory have generally been confined to situations that lie outside the useful range of carbon-14 dating. Because the radioactive half-life of carbon 14 is only 5,700 years, the carbon-14 method of isotope dating becomes increasingly unreliable when the sample is older than about 30,000 years. A case in point is the discovery in 1959 of fossil hominid remains at Olduvai Gorge in Tanzania by Louis and Mary Leakey. The hominid, which the Leakeys named Zinjanthropus, was at that time one of the oldest known; fossils associated with the find suggested that it might be a million years old, an age far beyond the range of any carbon-14 determination.

It happens, however, that the geological formation of Olduvai Gorge is a series of sedimentary rocks that includes numerous beds of volcanic tuff and ash. Some of the volcanic minerals are suitable for potassium-argon analysis, and so samples taken from volcanic strata generally related to the level in the gorge where the hominid remains were found were analyzed by Jack F. Evernden and Garniss H. Curtis of the University of California at Berkeley. They obtained potassium-argon determinations suggesting that the actual age of Zinjanthropus was almost twice as great as the associated fossils had indicated: about 1.75 million years.

Evernden and Curtis' finding might still be considered controversial (particularly because the mineral samples yielded a wide range of potassium-argon dates) if it were not for independent confirmation of their interpretation based on a fission-track analysis. Fleischer, Price and Walker undertook such an analysis, working with a specimen of pumice, the porous volcanic glass, from a related Olduvai stratum. The pumice was not easy to work with: the etched glass surfaces were small and irregular, and the etching solution actually dissolved away portions of the sample. Nevertheless, the investigators determined a fission-track date for the pumice: $2.0 \pm .3$ million years, a figure in close agreement with the potassium-argon determination of 1.75 million years.

At the other end of this anthropological spectrum one may consider certain man-made glasses that have uranium added to them in concentrations as high as one part per 100 in order to color them. Glass of this kind, which has been a standard item in Bohemia since the middle of the 19th century, can be dated by the fission-track method. Some students of Oriental art maintain that similar uranium glasses were produced in China centuries earlier. Günther A. Wagner of the University of Heidelberg has noted, however, that when a Chinese ring made of uranium glass, supposedly produced in 18th-century Ch'ing Dynasty times, was subjected to fission-track analysis, it turned out to be a 20th-century forgery, less than 70 years old.

Zircon crystals are natural components in some of the clays used to make pottery; any that are present in a piece of pottery are "reset to zero" when the pot is fired. The high temperature of the kiln erases all existing fission tracks. As a result the tracks that have been made in the time since annealing provide a precise indication of when the pottery was fired. Workers in Japan have been able to assign dates of manufacture ranging from about 300 B.C. down to 700 years ago to various pottery objects that contain zircon crystals. The dating of recently made pottery is tedious work, however; a very large number of tiny crystals must be scanned to get an accurate estimate of track density.



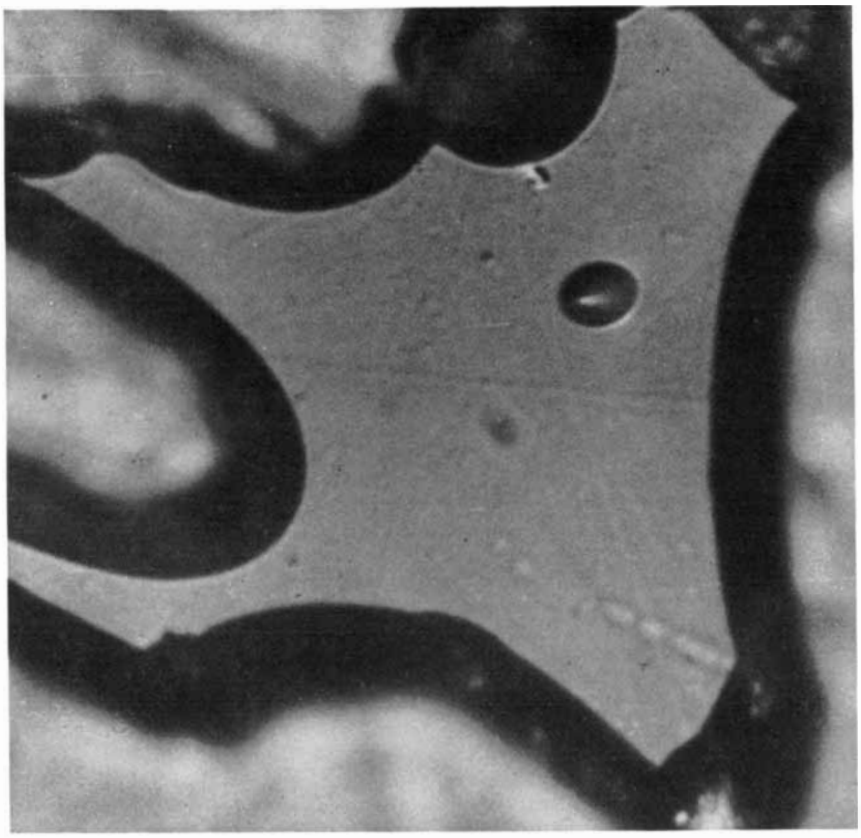
URANIUM CONTENTS of seven crystalline and two amorphous solids are compared. Man-made glass, colored by the addition of uranium oxide, is the material richest in uranium: from .1 to as much as 8 percent. Its date of manufacture can be calculated to within three years. Two crystals, olivine and quartz, may contain as little uranium as .1 part per billion. The age of such specimens, which may have crystallized three billion years ago, is hard to determine.

The mineral calcite, the hexagonal crystal form of calcium carbonate, has been found growing in the marrow cavities of old bones, among them the fossil bones of hominids of the genus *Australopithecus* unearthed in the limestone caves of South Africa. Some of the calcite crystals contain uranium in concentrations as high as a few parts per million. Price and I were working together in his laboratory at the University of California at Berkeley when we learned this a few years ago. We decided to see whether the fission tracks in the crystals might provide minimum dates for the fossil bones, since the crystals could not have formed in the australopithecines' marrow cavities until after their death.

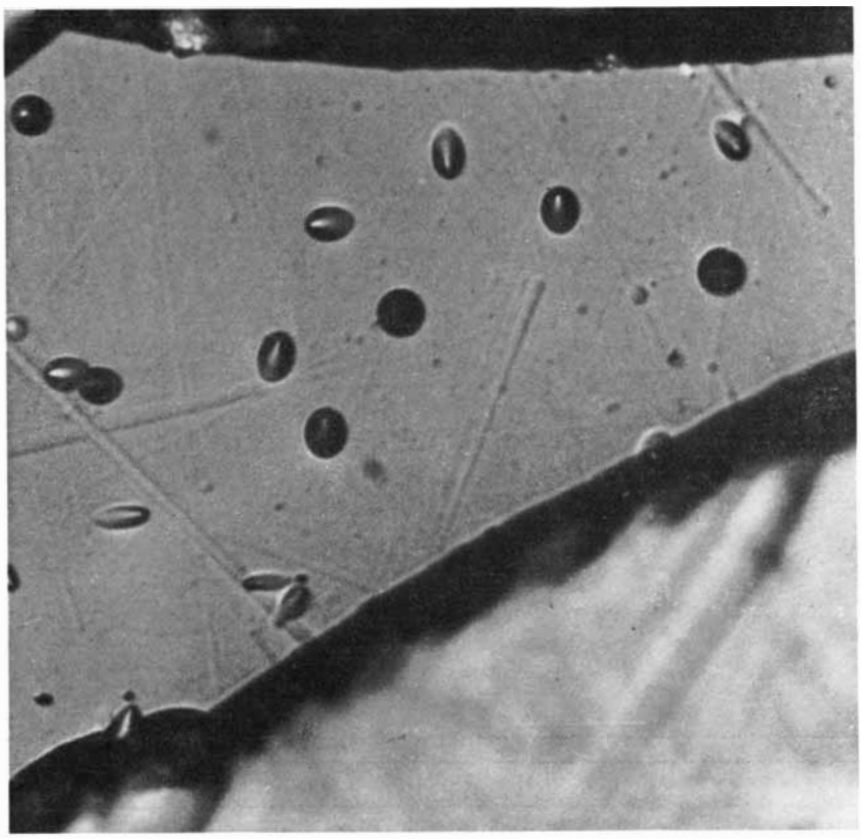
The spontaneous-track densities in the calcite crystals proved to be much lower than we had expected, suggesting that the fossil bones were by no means as old as other evidence indicated. When we conducted annealing experiments with calcite crystals in the laboratory, however, we discovered that the fission tracks in calcite are very susceptible to erasure. It appears that exposure to ambient temperatures over a period of a million years or so is enough to anneal existing fission tracks in calcite and thereby give rise to anomalously young age determinations. We have concluded that calcite will not be a particularly useful mineral in fission-track dating unless the crystals have been formed within the past few thousand years.

To turn to some of the less common applications of fission-track dating in geology, the differences between the annealing characteristics of various minerals provide a useful means of determining the geological history of such "thermal events" as the intrusion of a young igneous rock into an older igneous formation. An example is a recent study by L. C. Calk and C. W. Naeser of the U.S. Geological Survey. They collected a set of apatite and sphene crystal samples at closely spaced intervals along a traverse leading away from the line of contact between two igneous rock formations in Yosemite National Park: the Cathedral Peak granite and a much younger basaltic intrusion. Apatite is reasonably stable: exposure to a temperature of about 130 degrees Celsius over a period of a million years is required to anneal fission tracks in it. Sphene is even stabler: fission-track erasure in a sphene crystal requires a million years of exposure to a temperature of about 400 degrees C.

Calk and Naeser found that close to the zone of contact both the apatite and the sphene crystals from the older granite had been fully annealed at some time in the past. The crystals now showed fission-track ages identical with the age of the intrusive basalt: some nine million years. As the distance of the samples from the zone of contact increased,



VOLCANIC GLASS found in a layer of ash in a core of deep-sea sediments from the Pacific shows the scar of a single spontaneous fission track. Specimen is magnified 1,300 diameters.



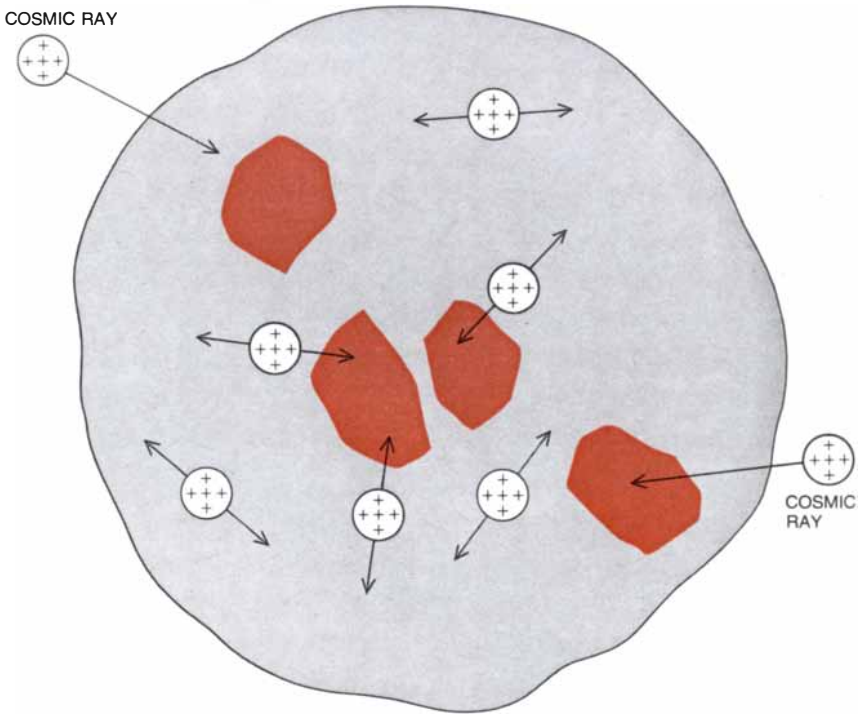
SECOND GLASS SHARD from a Pacific ash layer shows 20-odd fission-track scars; the tracks were induced by placing the specimen in a reactor and bombarding it with neutrons.

so did their fission-track ages. Within 10 meters of the intrusion the sphene crystals showed ages equal to the known age of the Cathedral Peak granite: 80 million years. The apatite crystals, more subject to annealing at lower temperatures, still showed some erasure effects 1,000 meters from the zone of contact. With the data from their sampling profile the two investigators were able to reconstruct the temperature record of this nine-million-year-old heating event.

Relatively few such studies have been conducted. It is nonetheless apparent that geothermometry based on the analysis of fission-track annealing will make it possible to decipher the thermal history of entire regions, particularly areas that have been affected by several episodes of heating. The fact that different crystals have different sensitivities to temperature changes, during episodes both of heating and of cooling, makes the analysis of fission-track annealing a powerful geological tool.

Fission-track dating methods are also applicable to marine geology. In the deep ocean, far beyond the zone where runoff from the continents affects bottom conditions, sediments accumulate on the ocean floor at rates as low as a few millimeters per 1,000 years. Our knowledge of the accumulation rates has been gained primarily through two radiometric dating techniques. One is the carbon-14 technique, which, as we have seen, is limited by the short half-life of the isotope. The other is the thorium-230 technique, which is more broadly applicable because Th-230 has a half-life of some 75,000 years. Even that half-life, however, means that samples older than some 300,000 years have lost almost all their original concentration of the radioactive isotope and can no longer yield useful age determinations. At the low rates typical of the accumulation of ocean-floor sediment the very first meter of a core sample of the bottom can span 300,000 years or more. Even the primitive coring devices of the 1950's brought up sedimentary sequences more than a meter long, and today the Deep Sea Drilling Project routinely recovers cores that are hundreds of meters long.

In some circumstances fission-track techniques can provide age determinations for such cores. The task is complicated, however, by the nature of the materials that make up deep-sea sediments. Apart from the shells of various dead marine organisms the principal constituents are particles of very fine-grained clays, generally silicates of aluminum, which are minerals that are not particularly suitable for fission-track dating. Fortunately another class of materials, the windblown debris from volcanic eruptions, is a fairly common component of the deep-sea sediments; even bottom cores taken far from land often contain discrete layers of ash: deposits that include relatively coarse-grained mineral fragments and volcanic glass that, having been flung high into the atmosphere by a volcanic eruption, were carried a considerable distance out to sea by prevailing winds.

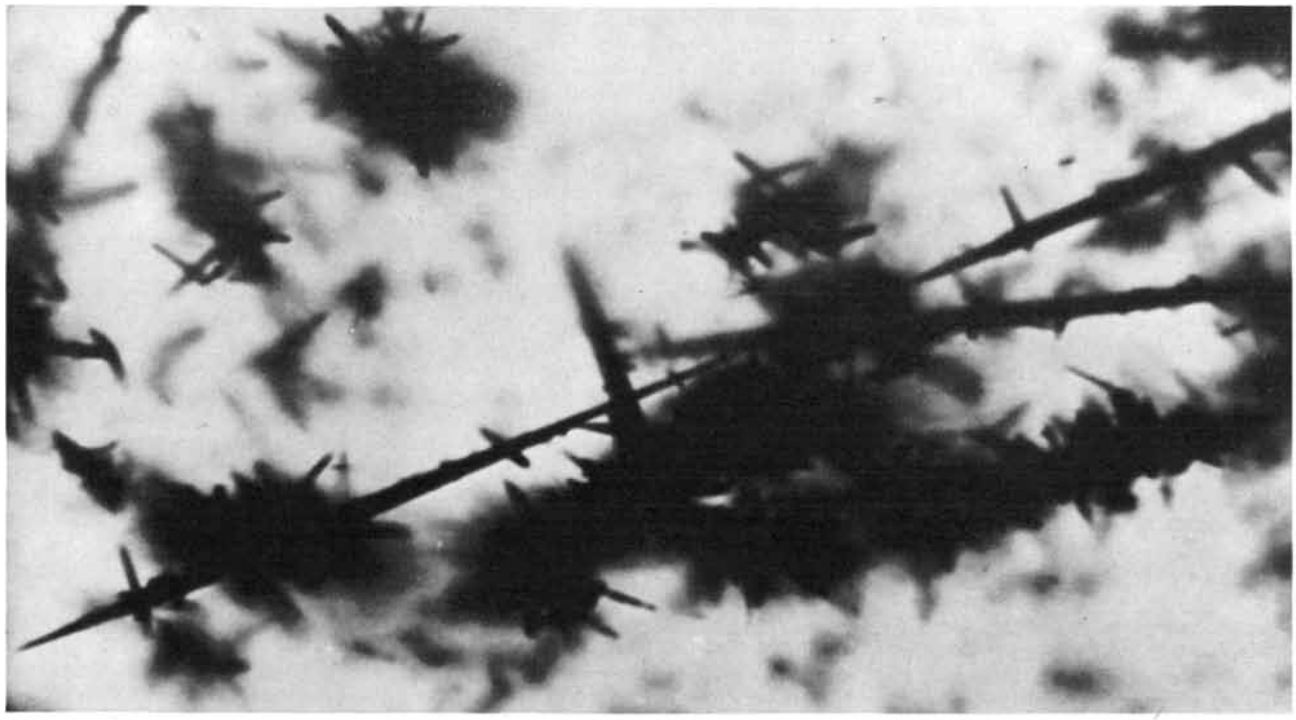


CRYSTALS OF OLIVINE scattered through the clay matrix of meteorites classified as carbonaceous chondrites are often completely lacking in cosmic-ray tracks (*left*) because the matrix shields them. The crystal surfaces, however, often show fission tracks (*center*) caused by the spontaneous fission of uranium and plutonium atoms contained in the matrix. Because such tracks could only have been formed after the clay and olivine came together to compose the meteorite, the "contact age" shown by the crystals also measures the age of the meteorite. Fission-track analysis suggests that some chondrites are substantially younger than expected.

Volcanic debris is not the only material of continental origin that can be found in deep-sea cores. It does, however, meet a criterion that minerals derived from continental runoff do not. The age of the runoff minerals is of course the age of the rocks from which the mineral fragments were weathered. The source rocks in turn may be millions or hundreds of millions of years older than the core stratum that contains their erosional by-products. In contrast, the interval separating a volcanic explosion from the time when the ejected debris sinks to the ocean floor is a trivial one on the scale of geologic time.

The products of a volcanic explosion are often quite rich in uranium. Moreover, some components of a deep-sea layer of volcanic ash are suitable for radiometric analysis by the potassium-argon method, which makes it possible to determine the age of the same ash stratum by two independent techniques. In my laboratory at the Scripps Institution of Oceanography we have used the tiny glass shards from deep-sea cores (actually the walls of bubbles formed in molten lava during a volcanic eruption) to get fission-track dates that agree closely both with potassium-argon results from the same ash horizon and with the chronological framework provided by the magnetism of the sediments themselves (which records periodic reversals of the earth's overall magnetic field). Other workers have successfully conducted similar studies with ash components from marine volcanic sediments that geologic processes have raised above sea level.

Even though some volcanic strata in the deep-sea sediments extend over thousands of kilometers, the ash layers are commonest in regions close to active zones of volcanism such as the Caribbean and the western Pacific. Their scarcity in (or total absence from) many central ocean regions means that fission-track analysis has limits in extending the range of absolute dating in deep-sea sediments. This is also true where determining the ages of sea-floor rock formations is concerned. The technique has been successful in dating the rocks of seamounts, those flat-topped volcanoes that rise from the sea floor to near the surface, particularly in the northern Pacific. For the basalts that constitute most of the ocean's rock floor, however, no entirely reliable means of radiometric dating has been found. The fission-track



TRACKS FORMED BY COSMIC RAYS in a crystal of olivine from a meteorite have been enlarged by etching and silvered to add optical contrast. The many short intersecting tracks mark the paths of iron-atom nuclei; the long tracks were caused by still heavier elements.

technique is stymied on two counts. First, the basalts contain very little uranium, and second, few of them incorporate any of the mineral crystals needed for fission-track analysis.

The spontaneous fission of uranium 238 is the only significant source of fission tracks on the earth. For the dating of extraterrestrial materials other sources of fission tracks, including one element that is no longer present on the earth in its natural form, come into play. The existence of these other fission-track sources makes it possible to date with surprising precision events that took place during the early stages of solar-system history.

The atomic nuclei known as primary cosmic rays never reach the surface of the earth because they are either deflected by the earth's magnetic field or absorbed in the atmosphere, or both. The nuclei, particularly the heavier ones, are capable, however, of producing tracks in nonterrestrial materials; these tracks are almost identical with fission tracks. Two such materials are now available to terrestrial investigators: meteorites and the mineral samples that have been brought back from the moon. The tracks left by cosmic rays in both kinds of sample are potentially a source of trouble when it comes to determining the sample's absolute age by fission-track dating. Nevertheless, if the analyst selects minerals with a higher-than-average uranium content and is also selective in his choice of sample material, it is possible to surmount the difficulty. For example, by using only interior samples, located at least 10 centimeters below the surface of a specimen, the analyst will find that crystals from this part of the specimen are relatively free of cosmic-ray tracks; the surrounding material has absorbed most of the track-forming particles.

When a meteorite sample of this kind is analyzed, it is not unusual to find that its absolute age, when calculated by the same method used for terrestrial minerals, turns out to be greater than the 4.6 billion years that represents the estimated age of the solar system. It is here that the element no longer found on the earth in its natural form enters the picture. It is plutonium. One isotope of plutonium, Pu-244, fissions spontaneously, and in very old samples of extraterrestrial material the isotope was once abundant enough to produce a measurable number of fission tracks. Even the oldest-known earth rocks are too young to have contained an appreciable amount of plutonium at the time of their formation, so that tracks produced by Pu-244 fission are not found in terrestrial samples.

The plutonium in the solar system, like the uranium, was originally manufactured elsewhere in our galaxy by the explosion of supernova stars. It was thus present in the mixture of materials that formed the sun and the planets. Where uranium 238 has a half-life of 4.5 billion years, however, plutonium 244 has a half-life of only 82 million years. As a result the plutonium isotope is no longer present in measurable quantities in any solar-system material. Nevertheless, in most meteorites and in some lunar minerals still retaining fission tracks that have accumulated over a period of more than four billion years, a significant number of the tracks were made by the spontaneous fission of plutonium 244.

On the reasonable assumption that the relative proportion of the spontaneously fissioning isotopes of plutonium and uranium was approximately constant in all solar-system materials it is possible to devise an age equation related to the ratio between the number of tracks left by plutonium 244 and the number left by uranium 238. Uranium and plutonium fission tracks are, however, physically indistinguishable. Therefore to determine the age of an extraterrestrial sample one starts by estimating how many fission tracks should be present in the sample on a dual basis: the measurable amount of uranium present and the amount of time that has passed. Since the amount of time is unknown at the start of the estimating process, successive iterations are necessary in order to arrive at a good estimate. The difference between the number of tracks attributable to uranium fission and the greater number of tracks actually present in the sample can then be attributed to plutonium fission, and the ratio between the two classes of tracks can be determined.

The method may seem subject to error if one fails to give full weight to the short half-life of plutonium 244. Actually over the period from 4.6 billion to

four billion years ago the number of tracks attributable to the spontaneous fission of plutonium shows a hundredfold decrease, compared with a decrease of only 20 percent or so in the number of tracks attributable to uranium fission. This makes the final result of the calculation quite insensitive to variations in the age finally chosen for the sample in the process of estimating the number of tracks attributable to uranium fission.

Because of the short half-life of plutonium 244 the ratio of plutonium to uranium changed rapidly early in the history of the solar system. The result is to make the method of absolute dating particularly sensitive for samples surviving from the period between 4.6 and 4.0 billion years ago. As an example, if one accepts the consensus that the ratio between the number of atoms of plutonium 244 and uranium 238 in any sample of the initially condensed matter of the solar system was .0154, the ratio of the tracks due to plutonium fission to tracks due to uranium fission decreases from 83 in a sample 4.6 billion years old to .6 in a sample four billion years old.

Most meteorites are at least four billion years old, and so they are good subjects for the precise age measurements based on the spontaneous fission of both plutonium and uranium. It has even been possible to determine the apparently different ages of minerals with different annealing characteristics within the same meteorite, so that a cooling rate for the entire meteorite can be reconstructed. The tracks of plutonium fission can also be observed in crystals of lunar material. The lunar rocks, however, tend to be younger than meteorites; most of them are less than four billion years old. As a result the plutonium-uranium track ratios are not as useful as they are with meteorites.

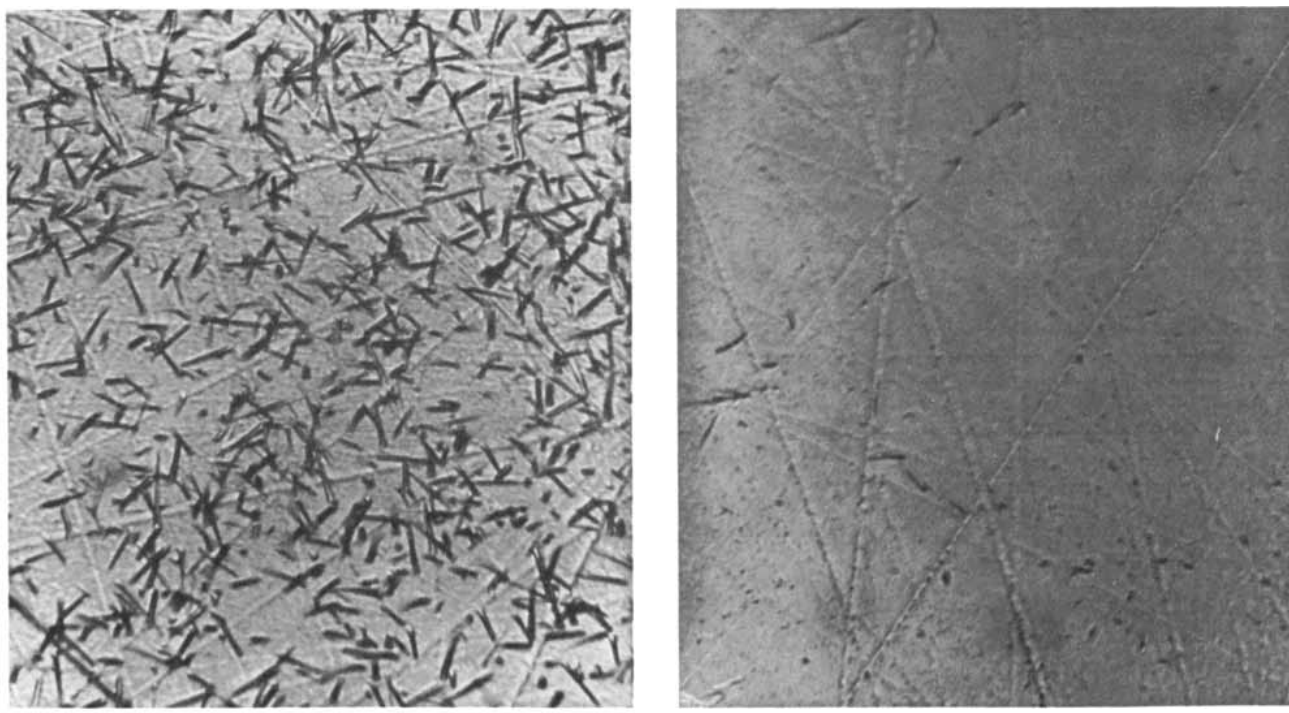
Among the seemingly primitive meteorites known as carbonaceous chondrites are some that consist of a claylike matrix containing larger mineral fragments and occasionally chondrules: crystalline spherical droplets that were probably produced by melting. The carbonaceous chondrites resemble terrestrial sedimentary rocks in that ordinarily an age determination, whether it is carried out on a gross sample or on carefully segregated components, should yield the age of the components rather than an indication of when the aggregate itself was formed.

Both Price and I noticed that the large, well-formed crystals of olivine embedded in the chondrites were virtually devoid of interior tracks. As far as fission tracks went, this was to be expected because the uranium content of olivine is very low. As for tracks produced by cosmic rays, their rarity in the crystals suggested that the carbonaceous chondrites had not undergone severe bombardment by these energetic nuclei. On the surfaces of the crystals, however, we found an appreciable number of fission tracks that had apparently been made by the fission of atoms present in the surrounding claylike matrix of the meteorite. The observation was consistent with the higher concentration of uranium (and at one time plutonium) in the matrix of the meteorites compared with the very low uranium concentration in the olivine.

The surface tracks could of course only have begun to accumulate after the two components of the meteorites had come into close contact. The observations therefore led us to the study of what we call the "contact ages" of the carbonaceous chondrites. By counting the fission tracks on the faces of the crystals we were able to determine a date for the formation of the aggregate, as opposed to the age or ages of its various components.

To our surprise, considering that in terms of mineralogical and chemical characteristics the carbonaceous chondrites have always appeared to be more primitive than the stony and iron meteorites, our analyses indicate that some carbonaceous chondrites were formed fairly late in the early history of the solar system: perhaps 4.2 billion years ago. The age of most stony and iron meteorites is close to 4.6 billion years. Where in the solar system were the materials that make up the chondrites parked during those 400 million years?

Those of us who work with the intriguing new technique of radiometric chronology that the fission tracks make possible continue to pursue this question and similar ones. Fission-track dating does not equal some of the older radiometric methods in precision, but it is likely that this situation will change. To me the most appealing aspects of the method are its simplicity and its frequent applicability where other absolute-chronology techniques are difficult or impossible to apply.



ANNEALING BY HEAT causes fission tracks to disappear as the disruption of the crystal lattice mends. An etched section of an apatite crystal (*left*) shows many fission tracks. After annealing, another section of the crystal (*right*) proves to be almost trackless when etched.

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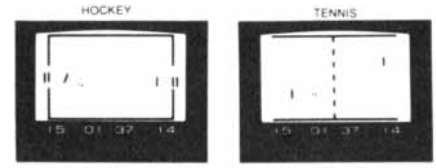

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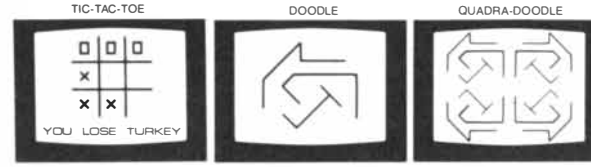

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MATHEMATICAL GAMES

In which "monster" curves force redefinition of the word "curve"

by Martin Gardner

When Zulus cannot smile, they frown,
To keep an arc before the eye.
Describing distances to town,
They say, "As flies the butterfly."
—JOHN UPDIKE, "Zulus Live in Land without a Square"

A fascinating aspect of the history of mathematics is the way that the definitions of names for classes of mathematical objects are continually revised. The process usually goes like this: The objects are given a name, *x*, and defined in a rough way that conforms to intuition and usage. Then someone discovers an exceptional object that meets the definition but clearly is not what everyone has in mind when he calls an object *x*. A new and more precise definition is then proposed that either includes the exceptional object or excludes it. The new definition "works" as long as no new exceptions arise. If they do, the definition has to be revised again, and the process may continue indefinitely.

If the exceptions are strongly counter to intuition, they are sometimes called monsters. The adjective pathological is often attached to them. This month we consider the word "curve," describe a few monsters that have forced redefinitions of the term and introduce a frightening new monster captured last year by William Gosper, a brilliant young computer scientist now living in Los Altos Hills, Calif. Readers of this department have met Gosper before in connection with the cellular-automata game Life. It was Gosper who constructed the "glider gun" that made it possible to "universalize" Life's cellular space.

Ancient Greek mathematicians had several definitions for curves. One was that they are the intersection of two surfaces. The conic-section curves, for instance, are generated when a cone is cut at certain angles by a plane. Another was that they are the locus of a moving point. A circle is traced by a rotating compass leg, an ellipse by a moving stylus that is stretching a closed loop of string around two pins, and so on for other curves generated by more complicated mechanisms.

Seventeenth-century analytic geometry made possible a more precise definition. Familiar curves became the diagrams of algebraic equations. Could a plane curve be defined as the locus of points on the Cartesian plane that satisfy any two-variable equation? No, because the diagrams of some equations emerge as disconnected points or lines, and no one wanted to call such diagrams a curve. Calculus suggested a way out. The word "curve" was limited to the loci of points that satisfy equations that are continuous functions.

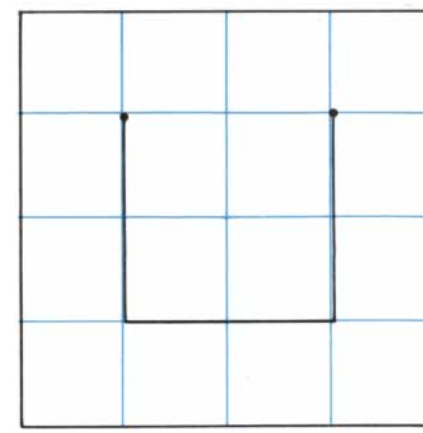
It seems intuitively obvious that if a curve diagrams a continuous function, it should be possible to differentiate the function or, what amounts to the same thing, to draw a tangent to any point on the curve. In the second half of the 19th century, however, mathematicians began to find all kinds of monster curves that had no unique tangent at any point. One of the most disturbing of such monsters was described in 1890 by the Italian mathematician and logician Giuseppe Peano. He showed how a single point, moving continuously over a square, could (in a finite time) pass at least once through every point on the square and its boundary! (Actually any such curve must go through an infinity of points more than once.) Peano's curve is a legitimate diagram of a continuous function. Yet nowhere on it can a unique tangent be drawn because at no instant can we specify the direction in which a point is moving.

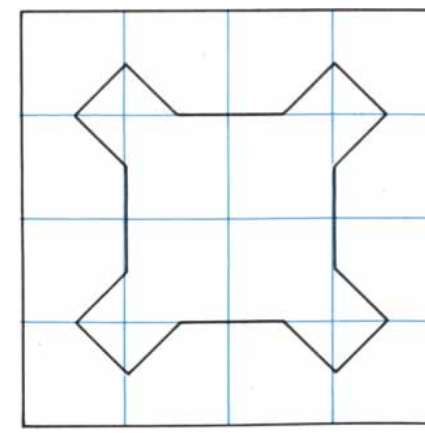
David Hilbert proposed a simple way to generate a Peano curve with two end points. The first four steps of his recursive procedure should be clear from the pictures at the top of the illustration at the right. At the limit the curve begins and ends at the square's top corners. The four steps at the bottom of the illustration show how Waclaw Sierpinski generated a closed Peano curve.

In both versions think of the successive graphs as approximations approaching the graph of the limit curve. This limit curve in each version is infinitely long and completely fills the square even though each approximation misses an uncountable infinity of points both of whose coordinates are irrational. (In general the limit of a sequence of approximation curves may go through many points that are not on any of the approximations.) Sierpinski's curve bounds an area 5/12 that of the square. Well, not exactly. The constructions approach this fraction as a limit, but the curve itself, the diagram of the limiting function, abolishes the distinction between inside and outside!

Peano curves were a profound shock to mathematicians. Their paths seem to be one-dimensional, yet at the limit they occupy a two-dimensional area. Should they be called curves? To make things worse, Peano curves can be drawn just as easily to fill cubes and hypercubes.

Helge von Koch, a Swedish mathematician, proposed in 1904 another delightful monster now called the snowflake curve. We start with an equilateral triangle and apply the simple recursive construction shown in the top illustration on page 126 to generate a crinkly





curve resembling a snowflake. At the limit it is infinite in length; indeed, the distance is infinite between any two arbitrary points on the curve! The area bounded by the curve is exactly 8/5 that of the initial triangle. Like a Peano curve, its points have no unique tangents, which means that the curve's generating function, although continuous, has no derivative.

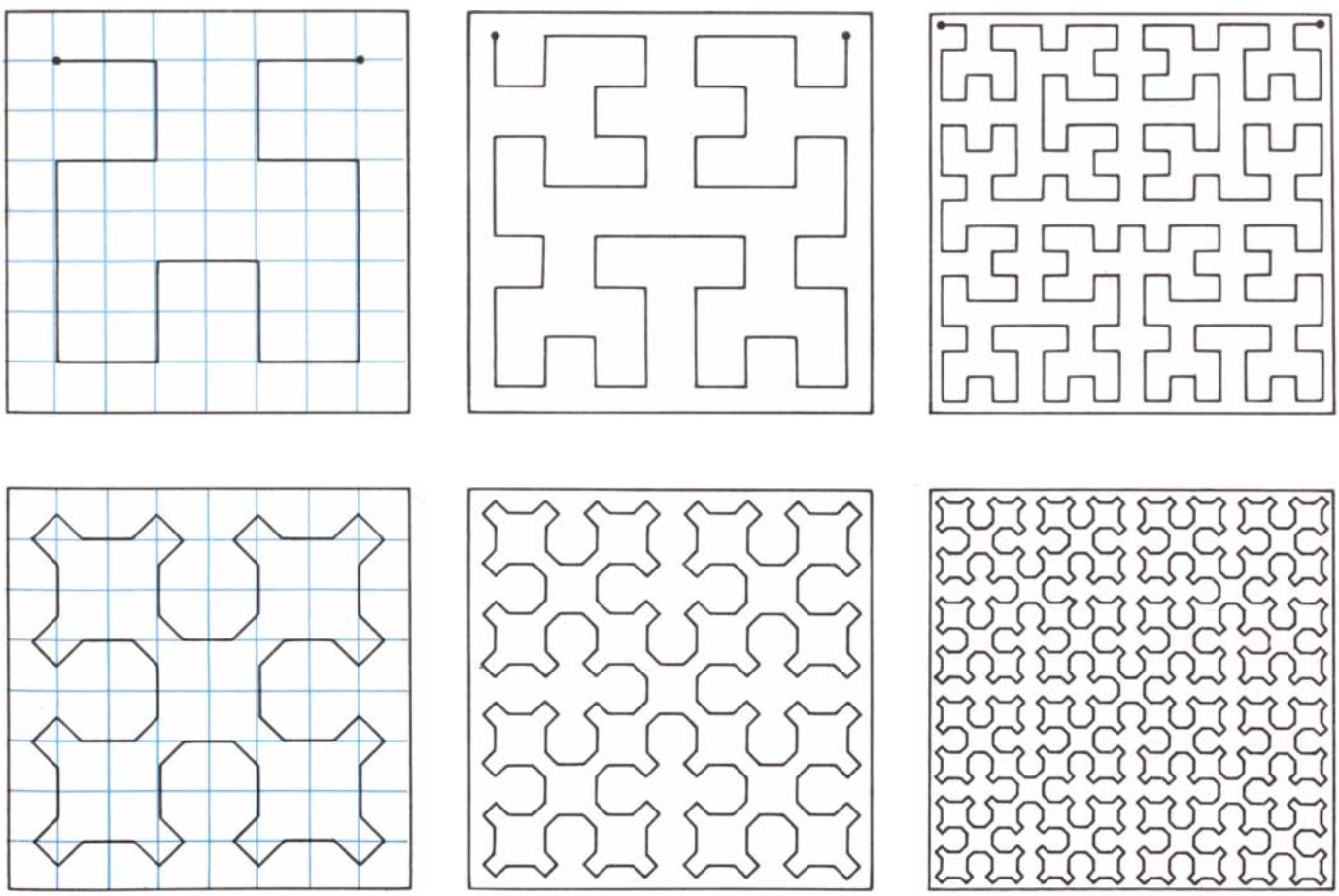
If the triangles are constructed inward instead of outward, one gets the anti-snowflake curve. Its perimeter is also infinite, and it bounds an infinity of disconnected regions with a total area equal to 2/5 that of the original triangle. One can start with regular polygons of more than three sides and erect similar polygons on the middle third of each side. A square, with the added squares projecting outward, produces the cross-stitch curve of infinite length that bounds an area twice the original square. (See my *Sixth Book of Mathematical Games from Scientific American,* Chapter 22.) If the added squares go inward, they produce the anti-cross-stitch, an infinite curve that bounds no area. Similar constructions, starting with polygons of more than four sides, produce curves that self-intersect.

A 3-space analogue of the snowflake is constructed by dividing each face of a regular tetrahedron into four equilateral triangles, erecting a smaller tetrahedron on the central triangle and continuing the procedure indefinitely. At the limit the prickly surface is infinite in area, yet it bounds a finite volume. The cube produces a similar analogue of the cross-stitch.

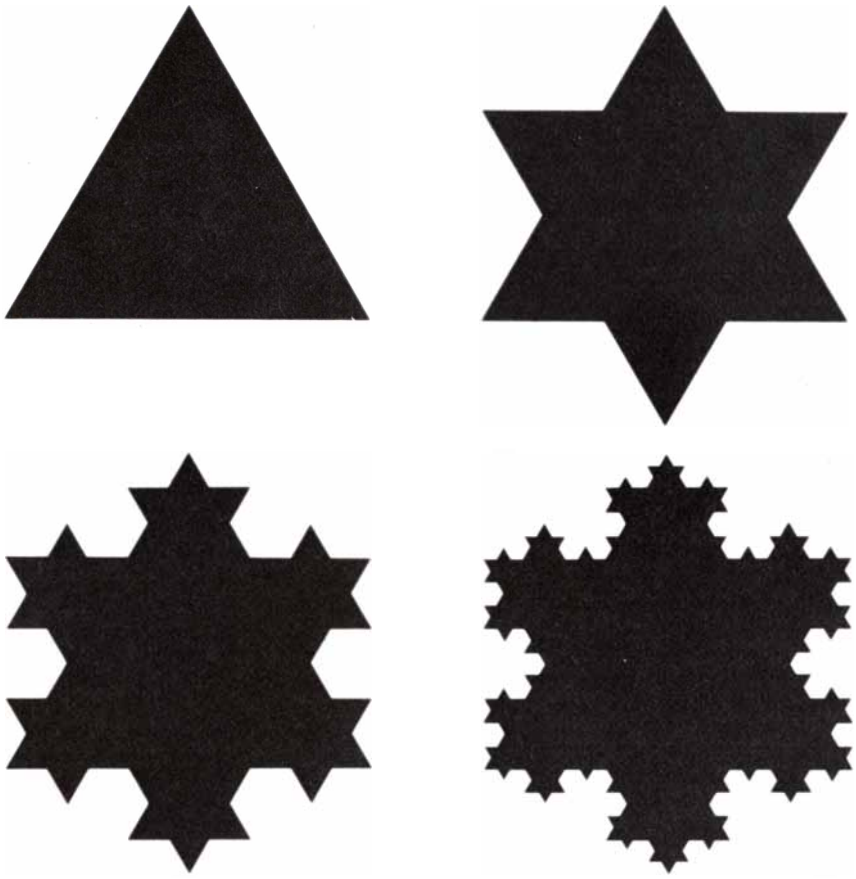
We can generalize further by dividing the sides of a regular polygon into more than three parts. For example, divide each side of an equilateral triangle into five parts, erect smaller triangles on the second and fourth sections and repeat to the limit. For an ultimate generalization begin with any closed curve that can be divided into congruent segments, then alter the segments any way you like, provided the alteration is segmented so that the change can be repeated on the smaller segments and carried to the limit. Analogous constructions can be made on the surfaces of solids. Of course, the results may be messy, self-intersecting curves or surfaces of no special interest.

A book could be written about other kinds of pathological planar monsters. The Dutch topologist L. E. J. Brouwer published in 1910 a recursive construction for cutting a region into three subregions in such an insane way that at the limit all three subregions touch at every point [see "Geometry and Intuition," by Hans Hahn; SCIENTIFIC AMERICAN, April, 1954]. Brouwer's construction generalizes to divide a region into n subregions, all meeting at every point. A more recently discovered family of monsters, the dragon curves, were introduced in this department in March, 1967, and were later analyzed by Chandler Davis and Donald E. Knuth in a two-part article in *Journal of Recreational Mathematics* (Vol. 3, April and July, 1970).

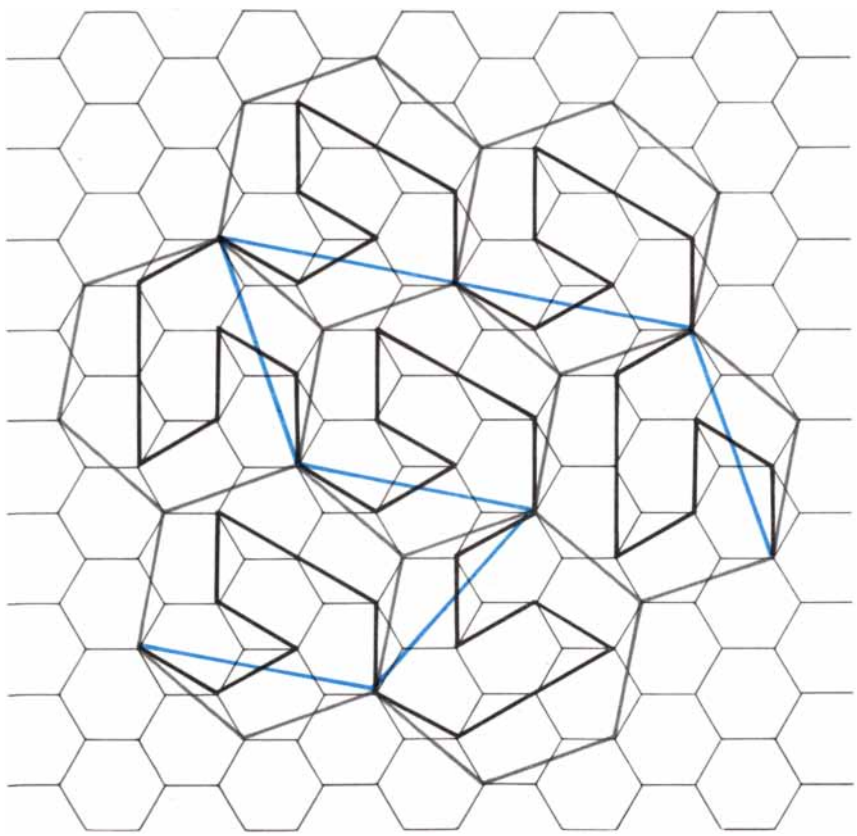
It is now my privilege to present Gosper's new monster, a beautiful space-filling curve he calls the flowsnake. Its construction starts with a pattern of seven regular hexagons [*see bottom illustration on next page*]. Eight vertexes are joined as shown by the colored line, made up of seven segments of equal length. The colored line is order 1 of the flowsnake. Order 2, shown in black, is obtained by replacing each colored segment with a similar twisted line of seven segments. Each segment of the black line is $1/\sqrt{7}$ the length of a colored segment; this



Peano curves: David Hilbert's open one **(top)** *and Waclaw Sierpinski's closed one* **(bottom)**



The first four orders of Helge von Koch's snowflake



Order 1* (color) *and order 2* (black) *of William Gosper's "flowsnake"

proportion holds at every stage of the construction.

The recursive procedure is continued to produce flowsnakes of higher orders. The illustration on the opposite page shows two computer drawings of flowsnakes of orders 3 and 4. By dividing the plane into black and white, with the bifurcating line passing through the flowsnake's end points, we see how the curve cuts the plane into two regions that twist about in almost, but not quite, the same pattern.

The curve that diagrams the limit of the successive flowsnake functions passes through every point of its region at least once, completely filling the space. The curve is infinite and nondifferentiable. Like the straight line, it is self-similar in the sense that if you enlarge any portion of it, the pattern always looks the same. Snowflake curves have the same property.

"Of course we have no physical snowflake curves," Philip Morrison has written. "Nature gives no infinities, not even within molecular collisions. There is a cutoff at the angstrom level. Still, surprises abound." By surprises Morrison means those random natural patterns that have, in a statistical sense, the property of self-similarity as successive enlargements are made. His remarks appear in a review [SCIENTIFIC AMERICAN, November, 1975] of a remarkable French book, ***Les Objets Fractals: Forme, Hasard et Dimensions,*** by Benoît Mandelbrot. A much-expanded version in English will be published next year.

Mandelbrot is a Polish-born French mathematician who is currently an IBM Fellow at the Thomas J. Watson Research Center at Yorktown Heights, N.Y. Like Stanislaw Ulam and many other eminent Polish mathematicians, Mandelbrot has had a career involving a marvelous mixture of creative work in both pure and applied mathematics, notably in physics and economics. His teacher, the French mathematician Paul Pierre Lévy, made the first systematic study of statistically self-similar curves, but they were regarded as useless, bizarre curiosities until Mandelbrot recognized them as being a basic tool for analyzing an enormous variety of physical phenomena.

Mandelbrot's forthcoming book is filled with pictures of just such phenomena. Consider coastlines. Their butterfly-flight irregularity is statistically self-similar. A coastline looks the same from a high altitude as it does from a low one. It is meaningless to speak of a coastline's "length" because it all depends on the precision of measurement. As Morrison puts it, "a coastline on maps at varying scales obeys a power law like the snowflake curve's, from a scale of hundreds of kilometers down to one of perhaps meters, where geography stops and pebbles begin."

The surface of the moon is another

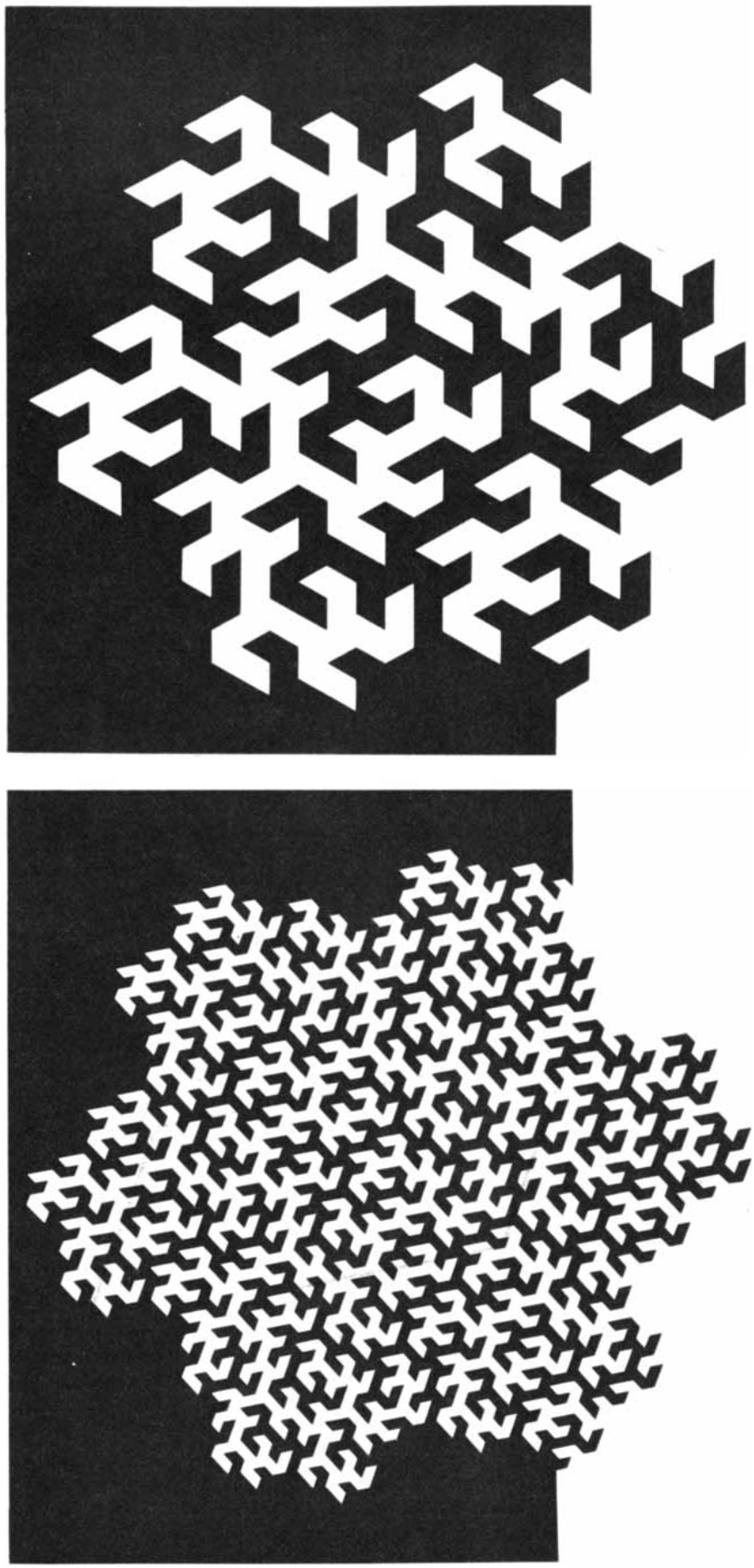
example. Remember your surprise on seeing the first closeup photographs of the moon made from a satellite in orbit around it? The moon's pocked surface looked basically as it did in photographs made with telescopes on the earth. Only the crater sizes were different. The same random self-similarity is found on the surface of certain cheeses, in the scattering of stars in the sky, in the contours of mountains, in atmospheric turbulence, in auditory noise and in countless other natural patterns. The Brownian motion of suspended particles approximates a statistically self-similar curve that (at the limit) has infinite length and no tangents.

Let us go back to the flowsnake for a close look at its perimeter and at an amazing paradox. The perimeter can be constructed by a recursive procedure much simpler than the one used to get the flowsnake itself. The top illustration on page 133 shows how it works. Start with a regular hexagon, then replace each side with a zigzag line [*color*] of three equal segments, each $1/\sqrt{7}$ the original side. The result is a nonconvex 18-gon. Since the zigzag line adds the same amount of area as it takes away, the 18-gon obviously has the same area as the original hexagon. Repeat the construction on each of the 18 sides to produce a 54-gon, and imagine that the recursive procedure is continued to the limit. At each step the number of sides triples, but the area never changes. At the limit the area filled by the flowsnake is exactly the same as the area of the original hexagon.

The entire region has an astounding property. It can be dissected, as is shown in the illustration on the next page, into seven subregions, each of which is an exact copy of the entire region.

Now for the paradox. What is the ratio of the area of a subregion to the entire region? Clearly it is 1/7, since seven identical subregions make up the whole. But let us approach it from another angle, remembering that the areas of similar figures are proportional to the square of their linear dimensions. If the boundaries of three subregions are bisected, as is shown by the line *AB* in the illustration, the six segments exactly fit the perimeter of the entire region. Clearly the boundary of a subregion must be enlarged by a linear factor of 3 to fit the boundary of the entire region. But if this is true, the areas must be in a ratio of $(1/3)^2 = 1/9$. We seem to have proved that the ratio of the areas is both 1/7 and 1/9. As Gosper asked when he first sent the paradox, *Vas ist los?*

The answer lies in the peculiar, counterintuitive character of the pathological boundary. There is no fuzziness about the area of the region it bounds. It is indeed seven times the area of a subregion. The boundary is not so well behaved. It is true that the boundary of a subregion is exactly similar to the over-



***Flowsnakes of order 3* (top) *and order 4* (bottom)**

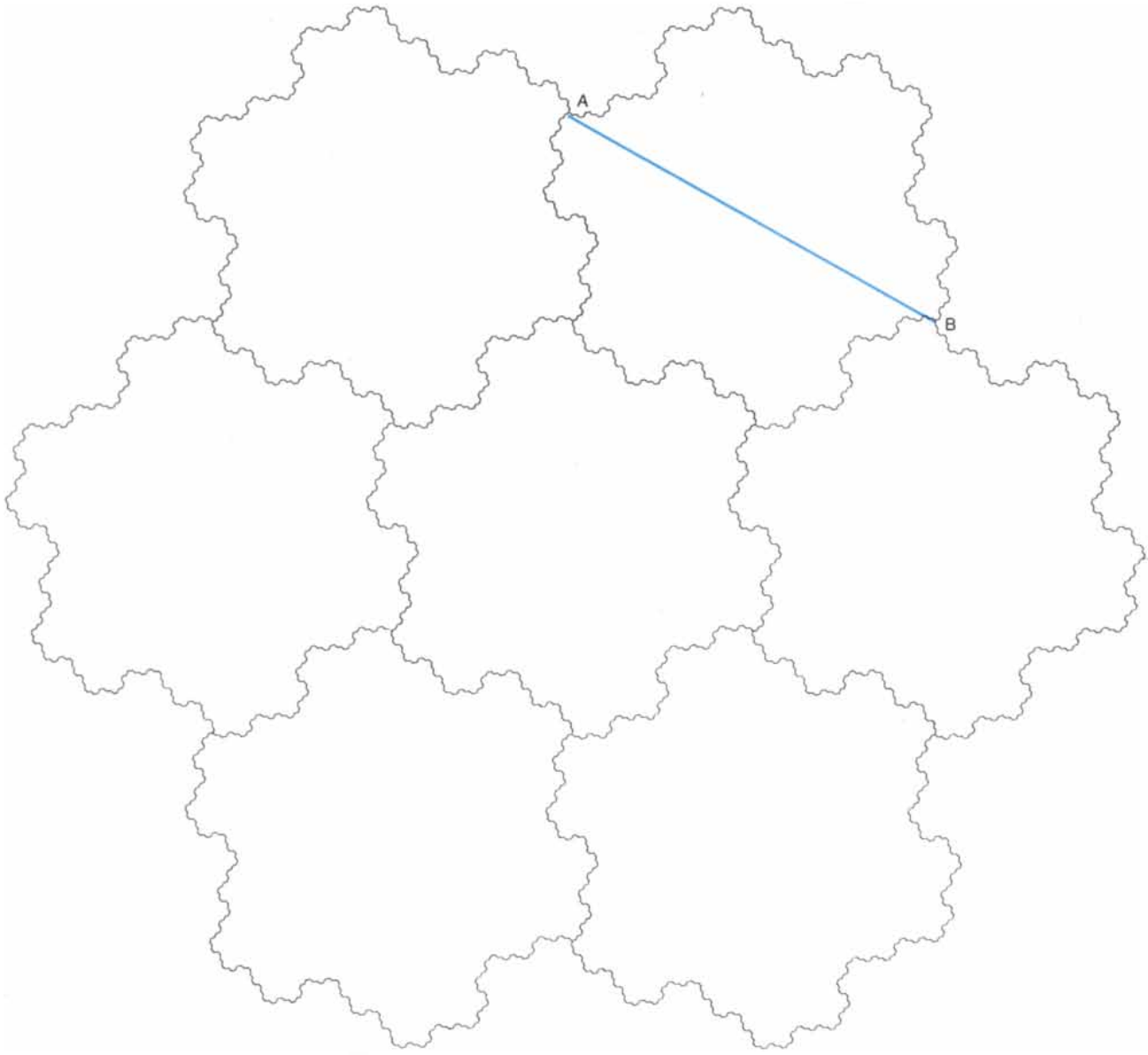
all boundary, but if the two are to be made congruent, the subregion must be magnified by a linear factor of $\sqrt{7} = 2.645\ldots$, not by a factor of 3 as it would appear.

A deep question now arises. What "dimension" should be assigned to the flowsnake's boundary? Like the snowflake, it lies in a strange twilight zone between one dimension and two dimensions. In 1919 a German point-set topologist, Felix Hausdorff, resolved the difficulty by giving fractional dimensions to such curves, or what Mandelbrot in his book calls "fractal" dimensions. They should not be confused with what are known as Hausdorff spaces, which are topological structures that mercifully we do not have to go into here.

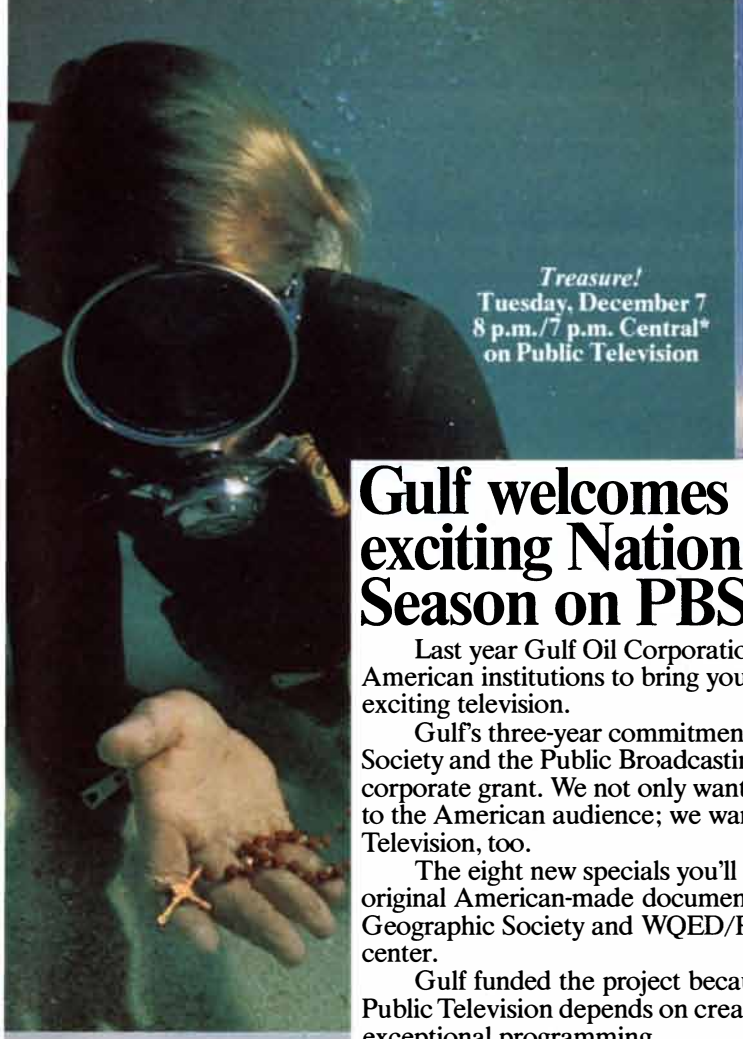
To grasp how fractal dimensions are calculated consider first a line segment. If we magnify it by a factor x, the magnified line can be cut into y copies of the original. The dimension of the line is the exponent of x that gives y. For the line segment in this case x equals y. For example, doubling the line produces two copies. The exponent is log (base 2) of 2, or $\log 2/\log 2 = 1$.

Magnify a square so that its edge doubles; the enlarged square can be cut into four copies of the original. In general if you magnify a plane figure by a linear factor x, its area increases by a factor of x^2. Its dimension is log (base 2) of 4, or $\log 4/\log 2 = 2$. If you double a cube's edge, the larger cube can be cut into eight copies of the original. Its dimension is log (base 2) of 8, or $\log 8/\log 2 = 3$. And so it goes for hypercubes in higher Euclidean spaces.

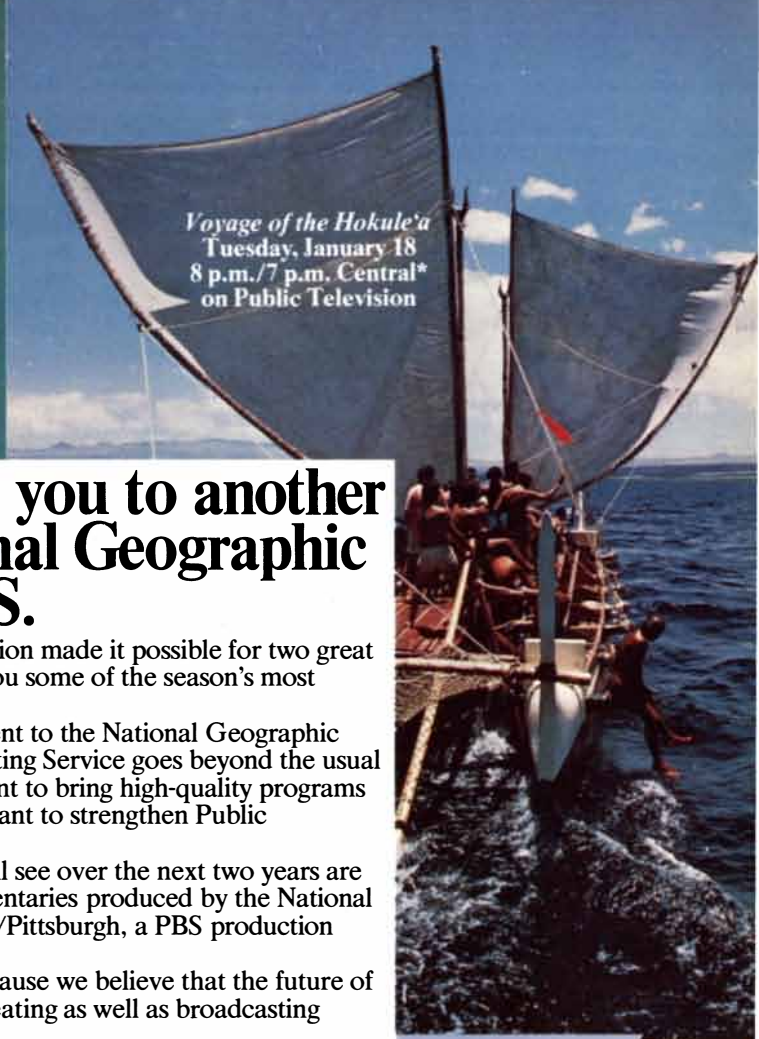
The snowflake is made by repeatedly replacing a line with one that is 4/3 as long. Thus it is reasonable to assign to the limit curve a dimension, called the Hausdorff dimension, that is log (base 3) of 4, or $\log 4/\log 3 = 1.26181\ldots$. The boundary of the flowsnake is constructed by repeatedly replacing a line with a zigzag path that is $3/\sqrt{7}$ as large. Its Hausdorff dimension is log (base $\sqrt{7}$) of 3, or $\log 3/\log \sqrt{7} = 1.12915\ldots$. It has infinite length, no area in units squared and a certain finite "size" expressed in units to the power of 1.12915.... Like all space-filling plane curves, the flowsnake itself has a dimension of 2 at the



A flowsnake paradox



Treasure!
Tuesday, December 7
8 p.m./7 p.m. Central*
on Public Television



Voyage of the Hokule'a
Tuesday, January 18
8 p.m./7 p.m. Central*
on Public Television

Gulf welcomes you to another exciting National Geographic Season on PBS.

Last year Gulf Oil Corporation made it possible for two great American institutions to bring you some of the season's most exciting television.

Gulf's three-year commitment to the National Geographic Society and the Public Broadcasting Service goes beyond the usual corporate grant. We not only want to bring high-quality programs to the American audience; we want to strengthen Public Television, too.

The eight new specials you'll see over the next two years are original American-made documentaries produced by the National Geographic Society and WQED/Pittsburgh, a PBS production center.

Gulf funded the project because we believe that the future of Public Television depends on creating as well as broadcasting exceptional programming.

We're also committed to bringing a wider audience to PBS. So we've provided funds to promote the National Geographic Specials on both a national and local level. Judging from the response to the first season, millions of Americans are now more aware of the exciting programs they can see only on Public Television.

Now we're ready for the Second National Geographic Season on PBS. We hope the millions who enjoyed the National Geographic Specials last year will be back this year.

It's another exciting season on Public Television.

The New Indians
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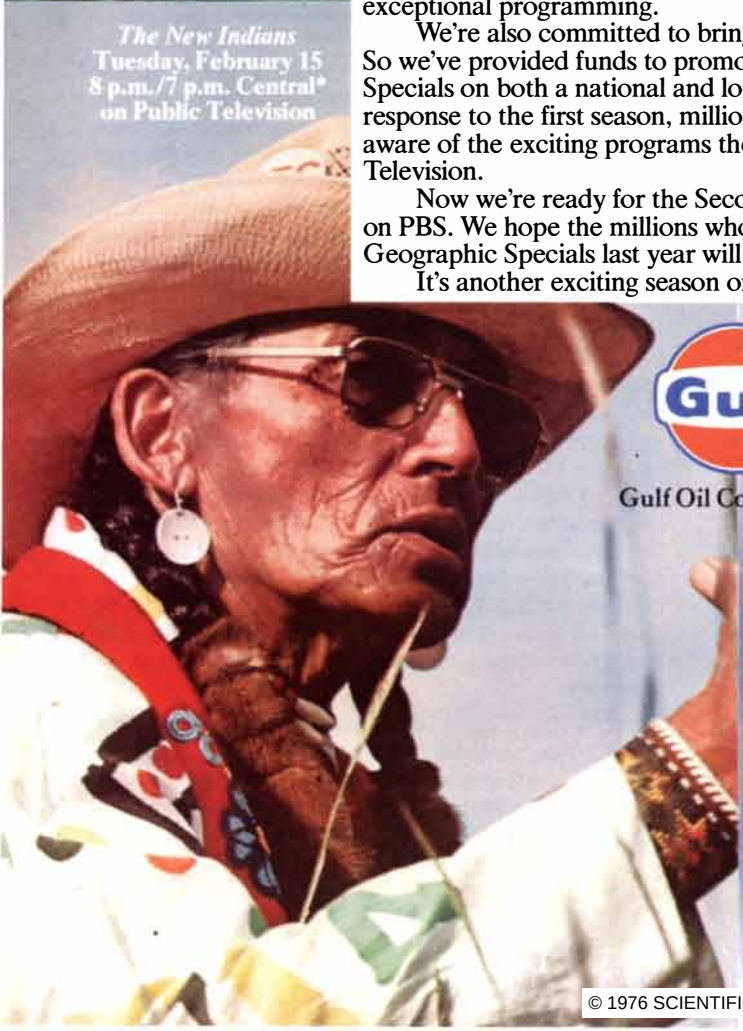
8 p.m./7 p.m. Central*
on Public Television



Gulf

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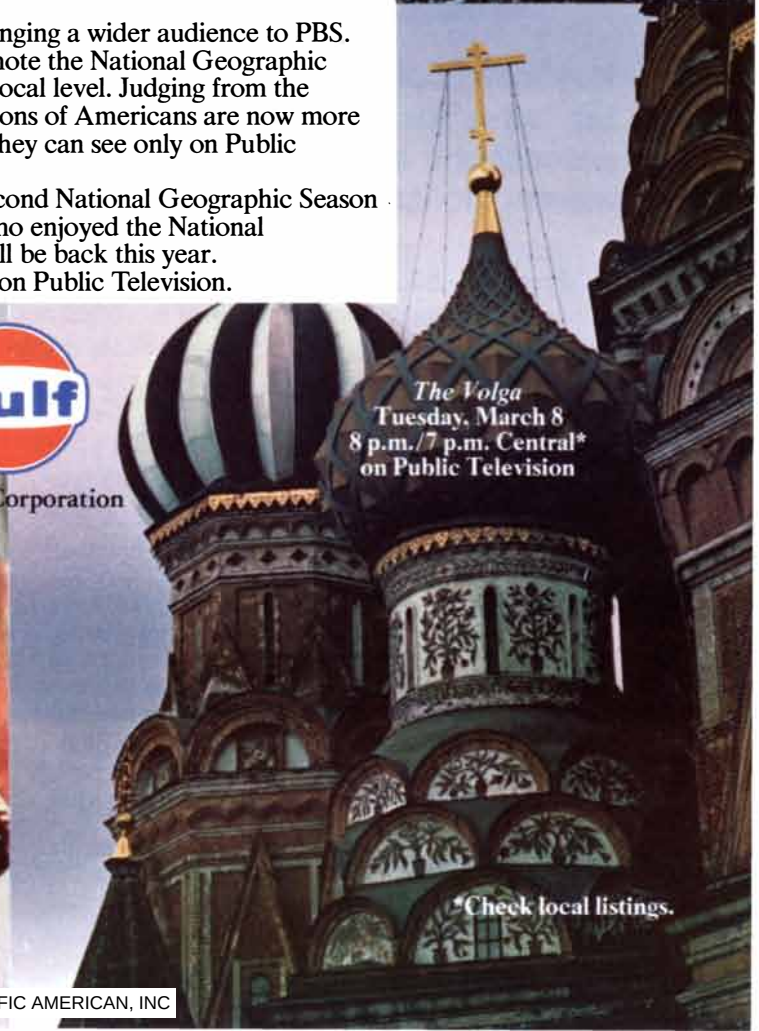
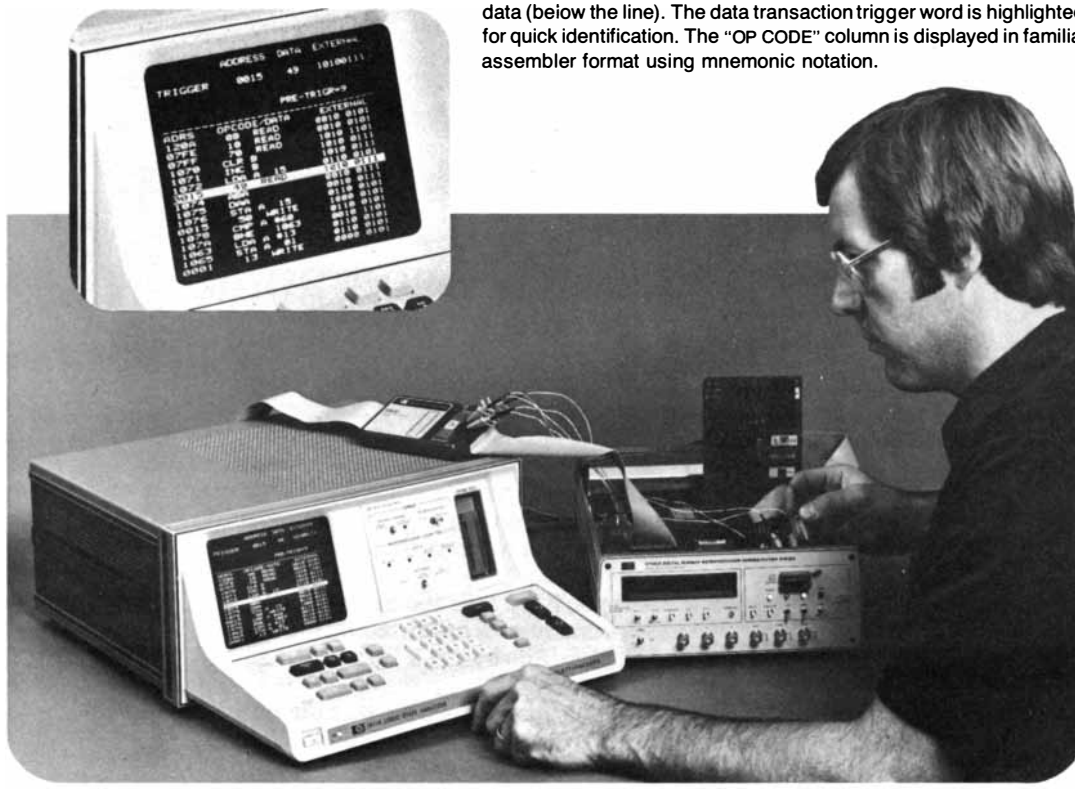


The Volga
Tuesday, March 8
8 p.m./7 p.m. Central*
on Public Television

*Check local listings.



Triggering parameters entered through the keyboard are displayed in alphanumeric format (above the dashed line) along with the collected data (below the line). The data transaction trigger word is highlighted for quick identification. The "OP CODE" column is displayed in familiar assembler format using mnemonic notation.

Keyboard control lets you set the terms for tracking a microprocessor's activity—in its own mnemonic language.

Designed specifically for debugging and troubleshooting microprocessor systems of the 8080 and 6800 families, HP's new 1611A Logic State Analyzer lets you pinpoint virtually any event or sequence in the execution of a program; it directly measures execution time between two keyboard-selected program points; and it easily performs analyses within other parameters that have been difficult—if not impossible—to achieve in the past.

As new applications for microprocessor-based systems proliferate, troubleshooting and program debugging are tasks that confront systems designers with increasing frequency. The 1611A greatly speeds and simplifies these tasks. A keyboard-controlled logic state analyzer, itself microprocessor-based, the 1611A has a "personality module"—special circuitry and microprocessor probe—that dedicates it to a particular microprocessor family.

The 1611A's triggering capability and alphanumeric CRT display let you look at nested loops, pinpoint I/O, ROM, or RAM activity, and find where a system went astray. You can limit the acquisition of data precisely to what interests you, and eliminate extraneous data. Furthermore, only the selected triggering parameters entered through the keyboard in either octal or hexadecimal format are displayed on the CRT—there is no need to look at a profusion of controls to determine test conditions.

Besides making the 1611A easy to use, its internal microprocessor permits the results of its measurements to be displayed in several formats. The contents of the address and data buses of the microprocessor system under test are captured in *real time*, and may be displayed in either octal or hexadecimal number base. The 1611A decodes the data bus contents into the mnemonic set of the microprocessor in the system under test, to provide a flow of information useful to the software writer who may not be familiar with octal or hexadecimal displays of his code. Or the display can be switched to an absolute format for step-by-step examination of program execution.

If you'd like a complete account of the 1611A's capabilities, write for our literature. The 1611A, configured for either 8080 or 6800 microprocessor-based systems, costs $5000 (domestic U.S. price only). Personality modules for other microprocessor families will be available soon.

Hewlett-Packard offers for the first time (ever) full-power APL on a relatively small general purpose computer.

The recently introduced HP 3000 Series II computer, whose powerful data entry and data base management signaled a price/performance advance in data processing, now adds APL to its language repertoire, accompanied by a new CRT terminal especially designed to operate with APL.

The advantages of APL among computer languages are becoming increasingly apparent. APL is a general purpose programming language, rich in primitive operators and formal identities, that uses powerful symbols in shorthand fashion to define complete functions in very few statements or characters.

APL offers highly beneficial shortcuts to data manipulation in scientific and engineering applications, where it can bring to bear its ability to express complex calculations in a concise way, and to operate on groups of numbers as easily as on single ones. Because APL normally operates directly on data without special commands, the novice can do useful work at once, freed from the necessity of learning complicated procedures that stymie nonspecialists.

By making an unabridged and enriched APL available on a relatively small computer, HP fills a price/performance gap that has frustrated potential APL users in the past: the full power of APL was available only on a massive computer or through costly service bureau time—or one settled for the limited APL capability of a "portable" computer.

Hewlett-Packard's enriched version of the language, APL/3000, actually broadens APL's capability to include the handling of large data bases, file manipulation, and production of reports in desired formats—placing APL squarely in the decision-maker's realm. And since the 3000 Series II computer treats APL/3000 as a standard language subsystem, any of its five other programming languages (FORTRAN, COBOL, RPG, BASIC, and SPL) can be used concurrently with APL in batch or interactive modes on up to 12 terminals.

Hewlett-Packard has developed a CRT terminal especially designed to handle APL symbols: the new HP 2641. Its versatile keyboard carries full APL and

standard ASCII character sets. Additional special function keys can be programmed to speed data entry and reduce opportunities for error. Optional minicartridge tape transports provide storage that allows the user to prepare data *off-line*, transmit it rapidly to the computer in batch, and keep or transfer development programs on the pocket-sized cartridges.

APL/3000 software and firmware can be purchased outright for $15,000. The 2641 terminal with 4 Kbytes of memory costs $4100; with tape transports it costs $5700. The 3000 Series II computer system, which makes it all possible, costs from $2350 to $7500 per month on a five-year payout lease, or $110,000 to $350,000 by direct purchase (domestic U.S. prices only, maintenance not included). We'd like to tell you more.

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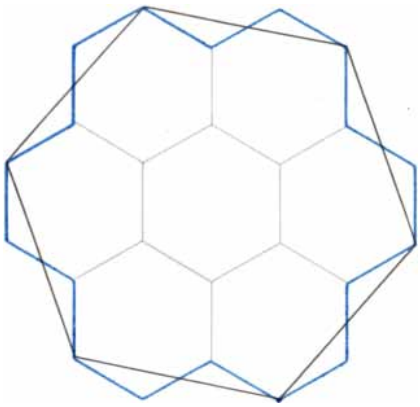


Making the flowsnake's boundary

limit because it completely fills a plane region.

As we saw above, an enormous variety of fractal curves that do not self-intersect can be produced by simple recursive procedures. So can fractal surfaces with dimensions greater than 2, fractal solids with dimensions greater than 3 and so on. The illustration below, reproducing one that is in Mandelbrot's book, is made by replacing lines of four units with lines of eight units (as shown at the top) to produce a squarish, asymmetric snowflake with dimension log 8/log 4 = 1.5. Since each alteration of a segment adds the same amount of area as it subtracts, the limit curve bounds the same area as the original square.

Note that the Hausdorff dimension is a measure of complexity. The square snowflake is more complex than von Koch's snowflake because its dimension is higher. Mandelbrot has been working with such curves for so long that he has acquired an uncanny ability to look at a new fractal curve and, by an intuitive estimate of its complexity, guess its dimension with high accuracy.

In the light of these crazy curves, how do mathematicians currently define a curve? The scene is so crowded with monsters that no single definition covers all the objects to which the word "curve" is commonly applied. The topologist defines a curve as a set of points that are compact, connected and form a one-dimensional continuum. To make the definition clear, however, a lengthy discourse on point-set topology would be required. The definition catches well-behaved curves that diagram functions with derivatives, but it misses some of the nondifferentiable monsters we have been considering.

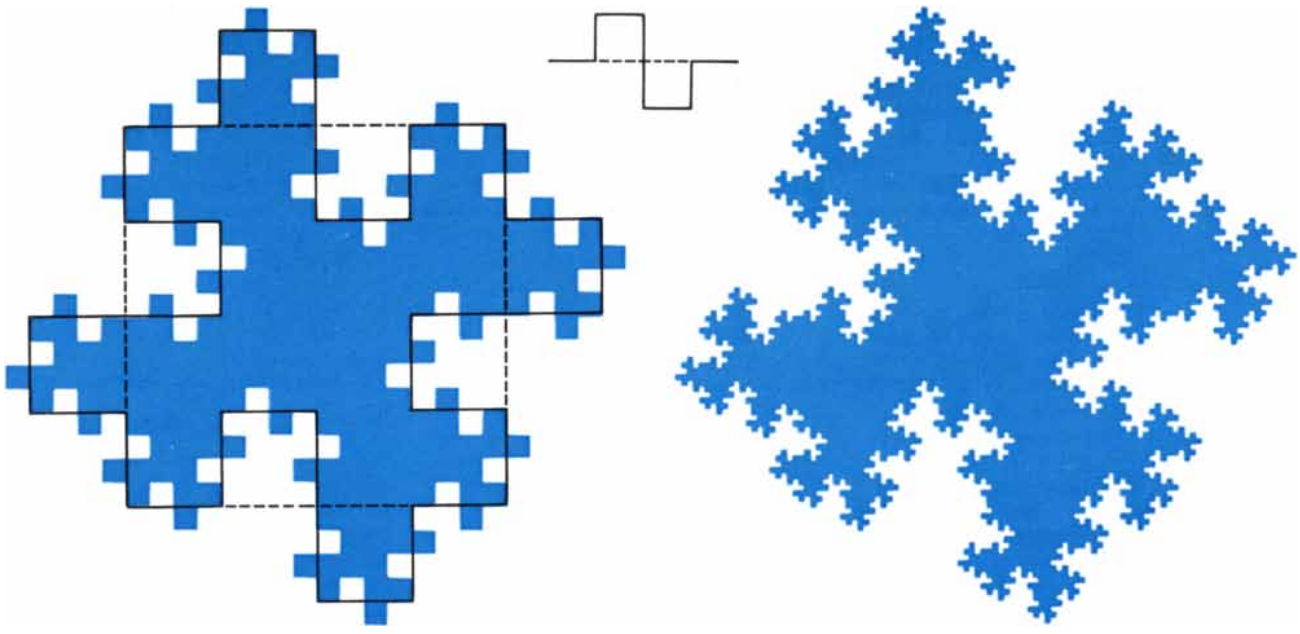
When attempts are made to define surface and volume, monsters more terrifying than flowsnakes crawl onto the landscape. This is a topic that must be postponed for a future column.

One of last month's problems was to guess how Dr. Matrix made a goblet of wine vanish inside a cylinder. The goblet was made of ice and was kept in its mold inside a freezer until Dr. Matrix was ready to perform. At the center of the table a small hole at the base of a slightly conical metal disk led into a hollow central leg. The disk was wired so that it became hot when Dr. Matrix pushed a concealed button on his desk. When the goblet melted, the water and the wine drained into the table leg.

It is easy to show how Dr. Matrix' formula of two variables, $(b + 1)/a$, generates a sequence of numbers that loops with period 5. Let a be the first number of the sequence and b the second. When the formula is applied recursively, the third number is $(b + 1)/a$, the fourth is $(a + b + 1)/ab$, the fifth is $(a + 1)/b$, the sixth is a and the seventh is b. The formula apparently was first noted by R. C. Lyness in *The Mathematical Gazette* (Vol. 26, 1942, page 62).

Many readers will be interested in two mathematically beautiful objects just placed on sale in the U.S. One is a splendid book on anamorphic art, profusely illustrated and with many color plates. Inserted in the book is a sheet of mirror paper for making a cylinder in which the distorted art can be viewed. The book, with the text by Fred Leeman, is titled *Hidden Images: Games of Perception, Anamorphic Art, Illusion—from the Renaissance to the Present.* Harry N. Abrams, Inc., is the publisher. It is a translation of a Dutch book that grew out of a major exhibit of anamorphic art earlier this year in Amsterdam. The exhibit is now touring the U.S.

The other item is an elegant but eminently playable chess set designed by Cy Endfield, heretofore available only in England. The silver- and gold-plated chess pieces are ingeniously cut at the top and the bottom so that they interlock to fit snugly over two cylinders. The leather-covered board, which folds into a box, has M. C. Escher's horse-and-rider tessellation on the squares. Around the sides is Escher's famous *Metamorphose,* a sequence of pictures that interlock much as the chessmen do.



The first three orders of Benoît Mandelbrot's square snowflake

BOOKS

An annual survey of books about science for children

by Philip and Phylis Morrison

Once more we offer the year's crop, a harvest of variety and substance. Again we note the powerful hand of fashion. Books on the physical sciences are few, obedient to the public taste. But physical experiences are the simplest for children, and they offer understanding within easy reach. The need for such a base of understanding remains as pressing as it ever was.

There is gain no less than loss. The flood of trendy ecological books has ebbed a little. The books we now see are deeper; they deal with the links among living things more concretely, with a clearer view, not one imposed as half myth on a sketchy account of the world. We believe they are the stronger and the more powerful for that.

Some Plants

CARING FOR TREES ON CITY STREETS, by Joan Edwards for the Environmental Action Coalition. Charles Scribner's Sons ($6.95). Carefully documented with on-the-spot photographs, this knowing little book is dedicated to the "Bedford-Stuyvesant Neighborhood Tree Corps, who first taught me about city trees." It is based squarely on the proposition that people need city trees (it tells why) and that city trees "need people as much as people need trees." Trees need care, just as teeth or cars do. In simple, short sentences we read what kind of care they need. They need loose soil free of garbage, cleansed of salt, watered, mulched and protected from dogs. A child—or a corps of children—can do all those things. Protection from dogs is a social problem, not a horticultural one, and guidance about tactful persuasion of dog owners is offered. Sometimes trees need more expert care, for pruning, filling cavities, bringing fertilizer. You can get it. If people want more trees, they must select and plant the right kind: supertrees, tough enough to make it on cement-covered and polluted city streets. Planning, cooperation and knowledge will help the trees and city kids as well. This book is an immensely practical guide. Adopt trees, map them, label them, make bark rubbings, accept responsibility, organize, learn and act. Trees, people and shared self-reliance can all grow in Brooklyn or any other city.

EXPLORING THE WORLD OF LEAVES, by Raymond A. Wohlrabe. Photographs by the author, diagrams by John F. McTarsney. Thomas Y. Crowell Company ($8.50). The huge oval leaves of the royal water lily float like rafts with upturned edges. Here we see the less familiar underside as well, a strong ribbed structure of support and nutrition that gives the entire leaf a curious resemblance in form to the back of the 200-inch mirror on Palomar. This book flows from the real experiences of the author in the botanical garden and the desert, in the forest and in the neighbor's backyard. He is a high school science teacher, and he has detailed here a series of simple experiments in plant physiology and tips for plant photography and the taxonomic collection of leaves and plants, all of which makes clear not only what teenage experimenters can learn but also the background in ecology, biochemistry and microstructure they need from "the literature." Around the theme he has set both exotic and curious plants and more familiar ones. The book will serve older readers who want to help younger ones experiment and explore for themselves. It is fun to extract the pigments and the essential oils from leaves; simple school science-laboratory equipment (described here with an emphasis on the safe use of heat, glassware and rubbing alcohol) can do all that and demonstrate as well the leaf's need for light and the phenomenon of osmosis.

CORN IS MAIZE: THE GIFT OF THE INDIANS, written and illustrated by Aliki. Thomas Y. Crowell Company ($5.95). The cobs are lined up across the page in a simple, clear drawing: popcorn, sweet corn, flour corn, flint corn, dent corn and pod corn. In 30-odd nicely drawn pages with lots of yellow and green tint and a very brief text the story of maize is told for readers in the early grades. Surprising in the richness of its content, this little book is notably engaging in its warm portrayal of Indian farmers north and south. Maize is a grass like the other grains, an early domesticate now entirely dependent on human beings. The drawing shows why: the fallen ear sprouts a crowd of competing seedlings. We see the long journey of the pollen tube down the strand of silk; the archaeologists in Bat Cave; tortilla, tamale and metate; the joyful ingathering dance of the Pueblo village; the gods of ancient times; a big harvester at work. The many ways one might encounter corn today are exhibited, from corn oil and corn syrup to glue and alcohol. The well-known artist-author has long had an interest both in corn and in American Indian culture; they have flowed together charmingly in this excellent little book, a model of economic ethnobotany for third-graders.

Some Animals

A CLOSER LOOK AT APES, by David Cook and Jill Hughes. Illustrated by Richard Orr. Franklin Watts ($2.95). WATCHING THE WILD APES: THE PRIMATE STUDIES OF GOODALL, FOSSEY AND GALDIKAS, by Bettyann Kevles. E. P. Dutton & Co., Inc. ($8.95). READING, WRITING, CHATTERING CHIMPS, text and drawings by Aline Amon. Atheneum ($7.95). *A Closer Look at Apes* is truly close. A slender book, with little text and big, bright paintings, this member of a new series published in Britain gives the impression of being a primer aimed at almost the youngest readers. The impression is dispelled by closer examination: the text accommodates graphs, diagrams of teeth and careful, simply written definitions and summations. The material is fresh. Consider the figures of four primates, orangutan to man, drawn side by side at one scale as though they had been shaved, so that the body form stands out. Humans are long-legged apes, not short-armed ones. The paintings are true scientific illustration. They are meant less to catch the eye than to exhibit in detail apes, generally in groups, engaged in some complex pattern of behavior. Here are a quartet of hungry chimpanzees dining on fresh meat and another group gathering fruit, obviously hampered by the lack of a bag, which they have not yet invented. The book is a first-class introduction to our cousins, suitable, like the other two, for readers from the middle grades.

In the Kevles book we are given a more complex view: ourselves watching. The chief actors are those women scientists, all recruited by Louis Leakey in the 1960's, who have become our best-known watchers, "courageous, perceptive and patient." The only time they all met was in a London apartment in the fall of 1971, in Leakey's last year. He never visited with Jane Goodall and Hugo van Lawick among their toolmaking chimpanzees on the shores of Lake Tanganyika, or with Dian Fossey high on the slopes of the Virunga volcanoes in Rwanda, where she lives nose-to-

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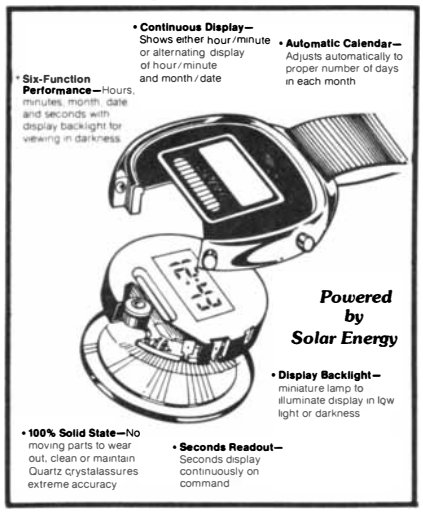

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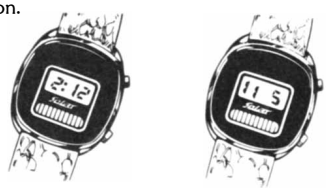

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peaceful-nose with the big, bluffing gorillas, or with Biruté Galdikas and her Canadian ex-physicist husband in the nature reserve in Borneo. There the little orphan orangs taken by the poachers are brought to be prepared for forest life. The "rehabs" are social enough, but the wild orangs the watchers seek out each day remain shy and solitary, using their evident intelligence "more to avoid intimate social contact than to seek it out." This book is a prize, because it gives us a good look not only at the distinct lives and careers of three young scientists but also at their current results, which are adequately published in accessible form only for the chimpanzee work.

This harvest of primatology is crowned by the Amon book, which offers an intimate account of some chimpanzees next door. Here are Washoe, Sarah and Lana, three chimps that have been adopted by cousinly humans and given entry into human language, according to one or another model of child rearing. Washoe of course became one of the family out there in Reno (Washoe County). She learned Ameslan, the American sign language. Now past 10 and mature, she lives in a chimp colony in Oklahoma, freely making signs to her less articulate companions. Sarah had a behaviorist education, manipulating plastic symbols for speech. She has left school, but her successors are hard at work. Lana was taught Yerkish by a computer, very trendily indeed. The work goes on; it is exciting to learn that the Nevada studies are being extended indefinitely by students recruited from colleges for the deaf, who use Ameslan fluently. There are plenty of ape students, and chimps study in public in the zoo at Portland, Ore. The book is fascinating and well illustrated, but it deserves the index it lacks.

The last word goes to the young Congolese with Fossey: "Awed at the sight of his first gorilla, he whispered, 'Surely, Lord, these are our relations.'"

ELEPHANTS, by Joe Van Wormer. E. P. Dutton & Co., Inc. ($7.50). WHITE GOLD: THE STORY OF AFRICAN IVORY, by Derek Wilson and Peter Ayerst. Taplinger Publishing Company ($9.95). Three dozen halftone photographs, mostly full pages, complement the simple, engaging text of *Elephants*. The pictures were mostly made in the field in Africa; they add up to a loving look at the great beasts, with the texture of trunk and hide, the happy bath in dry dust, the big herd rolling by with gleaming tusks, everything but the "rumble of massive digestive systems busy at work." The text scotches myths: elephants certainly do not fear mice, and it seems unlikely that they never forget. Although that huge foot with its great toenails is solidly planted on the ground, the animal has a way to manage a "fast walk," clocked at 24 miles per hour, the speed of a human Olympic-standard sprint. It is all a compact delight worthy of the splendid animals, suited to any good young reader.

Relations between the elephant and man do not, however, fit the idyll of the photographic safari. *White Gold* is a careful study (with interesting period illustrations) by two English writers with East African experience. It reveals us, the most cunning of social apes, as the artist-predators we are. Once we ate elephants; now Europe, Siberia and New Mexico hold only the tusks and bones of the vanished mammoth. In classical antiquity we hunted for ivory; no longer do elephants dwell north of the Sahara. The wealthy Roman Seneca owned "500 tripod tables with ivory legs." In populous India the chief use of ivory has been, and it is to this day, the marriage bangles of the young bride.

India has many elephants of its own; the craftsmen of China for a long time worked the tusk legacy of buried mammoths. Since medieval times, however, the elephants of Zenj—the black peoples' land—have furnished more and more of the glowing material for skillful carvers the world around. First came the Arab merchants along the coast and their heirs the Zanzibaris, who made the second half of the 19th century an epoch of bloody caravans of wantonly mistreated tusk-bearing slaves. Those were the days of H. M. Stanley, David Livingstone and Tippu Tip. Then came the white hunters and their legends.

The trade still prospers, even though large tusks are now a rarity. The game parks shelter uneasy crowds of elephants; there they do not grow old. It is not the swashbuckler or the poacher who dominates the trade in ivory today, but the national game departments that seek to manage the great preserves. Since May, 1973, there has been only government ivory for sale in the Mombasa auctions; Tanzanian tusks go directly to the Chinese carvers, and only in the Congo basin can hunters operate under loose control. The serenity of the warm ivory surface still attracts the craftsman and his sensitive client. Only billiard balls are no longer made of ivory; they must roll true, and the synthetic is more uniform. But high-quality piano keys, netsuke figures made by hand or by machine, the intricate ivory sculptures from the workshops of Peking and Foochow and the bangles and chopsticks of half the East still give incentive to our 10,000-year war against the elephants, while we steadily continue to take away their range for our own. This cool and comprehensive account of the irony that grips men and elephants is superb reading, although hardly for those young enough to hold illusions.

MONKEYS WITHOUT TAILS, by John Napier. Taplinger Publishing Company ($16.95). In this friendly, well-illustrated book a London professor of primate biology offers a "giraffe's-eye view," as that farseeing mammal might see human evolution "going on under (albeit a long way under) its nose. A giraffe sees man as a monkey without a tail, a rather ordinary primate." This conceit may be doubtful; indeed Professor Napier offers a postscript explaining that although giraffes are somewhat safer now from "being shot, stuffed and mounted," they are still under heavy threat from man's manipulation of their natural habitat, something the baboons and patas monkeys never did.

The book presents five chapters, each stemming from a lecture televised from the Royal Institution during a recent Christmas season, the series being the 141st of its kind. The live chimpanzee and the strong girl tearing the telephone book in half remain to us in photographs; we see in addition a couple of dozen color pictures of a zooful of our primate kin, plus a good deal more of apedom. The chapters include the zoo, an account of variation and natural selection, a survey of geologic time, a chapter on the apes and a final chapter on "the hallmarks of mankind," reduced perhaps a bit too sternly to what you can tell from old bones, which is hardly the giraffe method the author playfully began with.

Human genetic traits of handclasping, arm-folding, palm lines and the better-known PTC tasting are all described. There is also the story of Imo, a brilliant Japanese macaque whose two inventions swept through the culture of her troop; Napier sees her as a "simian Mary Quant." Imo first showed the way to wash sweet potatoes in the sea, and later how to separate wheat grains from sand by flotation.

The big toe is given its proper place as a key in the bipedal gait of human beings. The precision, power and hook hand grips are all discussed in some depth. The photographs include an interesting string of chimpanzee mug shots (the faces are quite different) and a white-faced flock of remarkably uniform purebred sheep. The BBC-television get-together of 300 pairs of identical twins in 1968 gave an altogether extraordinary sample of dittoed humanity; one photograph shows many of them clustered around David Frost in an image worth a good deal of study. This is a lighthearted and intelligent introduction to human evolution, accessible to any good reader in the upper grades and beyond.

THE CAVE BEAR STORY: LIFE AND DEATH OF A VANISHED ANIMAL, by Björn Kurtén. Columbia University Press ($8.95). Dragon Cave in Austria was singled out in early days as the repository of an enormous quantity of the bones of great creatures, plainly the prey of the unfriendly local dragon. By

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the 1930's the cave had yielded up enough carefully examined bones to make it clear that some 30,000 to 50,000 cave bears had died inside. Indeed, the abundant cave sediments were long mined for phosphate. The numbers are impressive, and many a scholar has seen in them evidence for a flood of bears, bears by herds and bears in droves, wandering over Europe during the warmer interglacial periods. The teeth and bones could be sorted: in the uppermost strata there were three big adult bears to be counted (mainly by canine teeth) for each small adult. The first theorists thought this showed the degeneration of the species; the 1,000-pound big bear was being joined by a dwarf strain. In the lower strata the ratio of big bears to small ones was equal, which could be explained on the basis of male and female bears but which would not work for the three-to-one ratio. In one dark passage were found 42 bear skulls and many long bones, which were rare elsewhere. Surely such a selection meant that some contemporary human cultists had chosen the bones for sacred preservation?

It is all fantasy, from the dragon on. This Helsinki paleontologist shows why in a splendidly straightforward little book, irresistible to naturalists young or old who enjoy the game of inference. The herds never existed, even though the cave bear was nearly vegetarian ("the least carnivorous of carnivores, and the most bearish of bears"). One family of bears each season and one dead bear every other year fit the actuarial statistics measured in the bones and make the cave appear to be a dragon's lair after a mere 100,000 years. The small teeth are those of adult females, all right; the numbers were biased in the count, and a she-bear looking for a quiet, snug place to rear her cubs is not attracted to such big caves, which are agreeable to ill-tempered males passing a lonely winter. (Counts of cub teeth show a male-female ratio of unity.)

For the story of the skulls so well selected and carefully preserved you will need to read the book. Suffice it to say that one cave held bear skulls in a kind of limestone chest made of slabs from the roof, yet even this can be explained most reasonably without human presence. There was a bear cult, but it came much later and was probably built around the brown bear. It is witnessed not by mere bones but by engravings, paintings and sculpture; the Great Bear of the skies is surely a brown bear.

Margaret Lambert has supplied convincing restoration drawings of long-gone animals and landscapes for this low-keyed book by a real expert who makes plain what evolutionary biology is all about. Professor Kurtén's first name means bear; he explains that no one escapes his fate. His happy fate has been to study cave bears for decades and to be able to build of those dry bones a gripping story of "the excitement of discovery; the grandeur of the past; the dynamics of life and death . . . and the enigma of extinction."

A NATURAL HISTORY OF ZEBRAS, pictures by Ugo Mochi, text by Dorcas MacClintock. Charles Scribner's Sons ($7.95). Once again this author-artist team has told the life of a hoofed animal of Africa. Ugo Mochi gives us a long, riveting look at zebras, zebras in repose, zebras in flight, zebras rolling over, zebras in foal and zebras in heat. He has cut each of these characteristic little forms out of a single sheet of paper with "agile fingers, and a small lithographer's knife," to make a silhouette that neatly evokes reality. Curved black bars on a white ground without outlines very convincingly display this striped world.

Zebras are of course horses: the two are together in one genus. The mammalogist-author admits that she is obsessed with horses, and she and Mochi have made a most horsey book, even if it is all about the three species of striped horses that decorate Africa today and a fourth that is no longer there: the quagga, a red-brown ponylike animal with stripes only in front of its shoulders. The quagga was hunted to extinction by Boer farmers more than a century ago. The last one died in the Amsterdam zoo in 1883; if zoos then had been as concerned with the breeding of endangered species as they are now, we could still admire the quagga. All that remains of the animal are a couple of dozen skins and three photographs, all of the same living specimen.

The most abundant of zebra species is the plains zebra; 150,000 of them, about a third of the total, daily pound the plains and open woodland of the Serengeti. The other species live in the mountains of southwest Africa or along the desert edges north of the Rift Valley. The familiar zebra of the circus and the zoo and the motion picture is the plains kind. These are social animals, unique among hoofed mammals for their stable family groups of one stallion, half a dozen mares and their offspring. Ethologists have found that three-quarters of the groups are unchanged over a period of two years (they know each animal by its unique variation in the striped pattern), and those mares that disappeared were probably taken by lion, dog or hyena. At night there is a watch; one member of the herd is alert while the others sleep. The families form into shifting herds of thousands, each herd with its favorite sleeping grounds.

The book is full of detail, much of it applicable to less stripy horses. The zebra is sharply adapted to a life of grazing and galloping over hard ground. One leg muscle has lost almost all its muscle fibers; it is a tendon spring with an action not unlike that of a pogo stick. ("The harder the impact, the higher the bounce.") The stripes remain an enigma. It does seem that the older zebra forms were a dark solid color on which the white stripes evolved. But why? Are they camouflage, dazzle painting, a recognition signal or heat control? Here we see a pair of zebras that look like a photographic negative and its positive; one animal has wide black stripes with narrow white interspaces and the other has the reverse. This definitive book cannot miss pleasing anyone fond of horses or of zebras who is old enough to read in some detail about the facts of life.

Living Chains

MILKWEED DAYS, by Jane Yolen, with photographs by Gabriel Amadeus Cooney. Thomas Y. Crowell ($5.95). DIARY OF A MONARCH BUTTERFLY, by Susan L. Thompson. Graphic design by Sas Colby, with detail drawings by Judy LaMotte. Magic Circle Press, distributed by Walker and Company ($6.50). THE MILKWEED AND ITS WORLD OF ANIMALS, by Ada and Frank Graham. Photographs by Les Line. Doubleday & Company, Inc. ($5.95). In the sweet-smelling meadow behind the barn the milkweed plants grow so high late in the summer that a small boy disappears in them. The rough pods hold a cloudy secret; once the silk is revealed the children catch on and blow it again and again. It is September snow that a boy can recall all winter long, with one unopened pod kept to help him dream of sunny milkweed days. *Milkweed Days* is a small, poetic tale given force by the evocation of that meadow and the children in admirable black-and-white photographs. To this book with its brief and simple text the other two add a deeper, more studied world, the world of life that dwells on the milkweed.

The Thompson book is also one of brief text, written as a journal of a summer month in which two girls of school age are drawn into the enchanted development of a monarch butterfly step by step from an egg on a milkweed stalk to a flight over the field of milkweed to the horizon. The illustrations are strong silhouettes of the girls and their careful work, enhanced by detailed drawings in line and stipple that give a closer view of the hungry caterpillar, the jeweled chrysalis and the triumphant butterfly.

The Graham book cuts a wider swath for older readers, again with splendid large photographs of the milkweed meadow. Many insects are part of the meadow's web of life, and the book tries to make plain how the qualities of the milkweed fix the lives of the monarch butterfly and the milkweed beetle, the aphid and the ladybug, the ant and the honeybee, the katydid, more butterflies still and a legion of spiders. Some macrophotography takes us into this small world, and we are told about the spread

of a radioactive tracer (quite safe in amount) through the insects and plants as it is measured by Jim, "a scientist who comes to the meadow" and helps us to realize how many families of insects live there. The text, outweighing the pictures but still never taxing, presents by concrete example the grand ecological view of the flow of matter and energy through a part of the living world. Seeds and eggs alone remain to overwinter aboveground, the legacy of the milkweed patch that sleeps below, a complex system of roots ("really one huge plant") that will nourish the cycle again once the sun of spring returns.

KNOWING THE OUTDOORS IN THE DARK, by Vinson Brown. Illustrations by Phyllis Thompson and others. Collier Books ($2.95). Sit still and watch in the dark! Forty-five minutes for dark adaptation, the use of starlight or moonlight (sometimes with help from snow) and much practice in your backyard, and you can wander slowly through the "frightening dark masses" of the night without fear and with a deepening sense of meaning. Woods, meadow, desert and beach are all alive by night. One who prepares can come to know that life. The branch tips of a Douglas fir "seethe in the wind like octopus tentacles," and the carefully filtered red flashlight you may want to carry shows now the small orange-red eyes of the noctuid moths on the tree trunks, now the fiery white eyes of a coyote. There are the strange falsetto cries of the male porcupine at mating time and the acrid musky odor of a badger. Odors are better sensed on a damp night with a nose held low to the ground.

You do not have to muster that much courage. It is possible to watch from a comfortable porch or from a chair on a small platform in the desert, its feet standing in cans filled with oil, proof against the venomous creatures of the Sonoran night. Keep vigil beside a night-blooming plant, from the giant cereus to the evening primrose, and you will watch and smell a sequence of hidden wonder in the desert and in a city park. The lonely seashore offers the endless sounds of the sea, like "the long breathing of a great sea monster," maybe the remorseless sun star forcing open its clam prey or the flower animals of the low-tide pool, revealed by flashlight beam in a new richness always hidden from the sun's heat and the gull's daytime search.

The subject matter of this book is admirable; the adept author has made a path to a new world right at hand. The form is less so: the organization by habitats is somehow fragmented, the drawings are often tiny and the many lists of species seem a bit padded, even though most of the entries are connected with the special nocturnal viewpoint. The writing is clear enough, and from time to time achieves the poetry the author plainly feels. The book should be a stimulant and a guide to any young naturalist old enough to stay up well past midnight once in a while, and brave enough to sit quite still, near a friend perhaps, in the wild darkness. Here we are beyond the dream of Maurice Sendak's Max; the place where the wild things are moves outside.

WINDOW INTO A NEST, by Geraldine Lux Flanagan and Sean Morris. Foreword by Niko Tinbergen. Illustrated with photographs. Houghton Mifflin Company ($7.95). SCIENCE PROJECTS WITH EGGS, by David Webster. Illustrated with photographs in black and white and drawings by Rod Slater. Franklin Watts ($4.90). A casual remark by the distinguished biologist who writes the foreword for *Window into a Nest* started it off. Pretty soon the filmmaker Sean Morris had put the idea to work. A house window in Oxford was boarded up around a small wood birdhouse, its entrance hole the size of a 50-cent piece. But the birdhouse, or nesting box, had no back; that wall was the window glass. Black curtains made a kind of dark tent inside the window, keeping out the light from the room. Morris and his partner, the author of a much-praised children's book on the development of the chick, could enter behind the curtains and view the nesting box as though it were a little theater lighted only by daylight coming through the entrance hole. It turned out that even flash photography did not disturb the birds much, and of course photographs could also be made by natural light. The book records a remarkably complete and intimate view of family life of "shy woodland birds living undisturbed in their nest." Indeed, in addition to the 2,000 photographs made for the book, an entire motion picture was shot over the same three months.

The bird pair were blue titmice, a kind of chickadee. They entered in February; in June a thriving family of seven fledglings left the nest to seek their fortune in the world outside. During that time the excited authors and their friends watched the daily drama for hours on end, seeing the first coming together of the male and the female, their stern defense of their new territory, the arrival of spring (when the male began to feed the female), nest building, mating, egg laying and the time of incubation, until 10 speckled eggs hatched seven voracious little birds. (Three other eggs remained unbroken and ignored.) Then the parents fetched up to 1,000 caterpillars a day and removed the waste pellets as their chicks grew. One fine day it ended. The oldest and boldest chick left first, called by the male high on a tree outside. One by one the rest followed, until only one of the two youngest and smallest birds was left. "The empty nest may have seemed a stranger place than the space outside where the familiar voices called. The last one went up to the nest hole and without any hesitation at all it flew out and up, calling all the way 'here I come . . . here I come . . . wait for me!' "

The text is rich with a careful biological account, from hormones to behavior signals, but it is so devotedly written, so close to experience, that it carries in the tale of the nest a considerable charge of human concern. Human parents also bond and rear, and children leave the care of home and parents in their time. The parallel is real, even though we are not birds; our lives are more subtly patterned. Yet the remarkable story and its images give this book a unique flavor; it can be read by children in the middle grades and beyond.

Science Projects with Eggs stands in a way for the cool biology of the laboratory or the farm, as opposed to the empathy of *Window into a Nest*. Eggs have a shell and a structure, parts and properties. Fertilized eggs (not those from the supermarket) can be hatched, and instructions are given for making an incubator out of a Styrofoam ice chest and the requisite electrical fittings; it costs about $25. Hatching chicks is a wonderful task, even without the parents at hand; the study of embryo development is more difficult but most rewarding. The book is a brief guide to a dozen such projects, some as easy as candling, and it invites action by both younger and older grade school children or class groups.

People

THE MOUTH OF THE NIGHT: GAELIC STORIES RETOLD, by Iris Macfarlane. Illustrated by John Lawrence. Macmillan Publishing Co., Inc. ($6.95). One hundred and twenty years ago J. F. Campbell and his collectors walked about the Hebrides Islands, seeking stories told in the Gaelic, stories passed without writing down the generations by word of mouth, from the same lode worked by the brothers Grimm. From memory the people "told night-long stories, without pause or hesitation or repetition." These were translated and published in a book that is now a classic for the folklorist but is too taut and bloody for a child to read with much pleasure. The author is herself a folklorist and a resident of the Outer Hebrides; she has retranslated 14 of Campbell's fine stories, softened them a little, sorted and linked. "Something is lost, something is always lost," but the stories are now accessible. Original drawings, strong, wry and fanciful, well illustrate these stories, which carry the song of time in a book whose form and matter earn it the right to be called distinguished.

A review cannot do justice to one story, let alone 14, but consider the famous hunter Murachag Mac Brian, who lived on the Plain of Pebbles. Lost in the mist,

he encountered a little man with a brown cap on his head. The courteous woodman took Murachag home, where he sat in a chair of gold while Murachag sat in one of silver and stared at the woodman's wife, a woman of great beauty. The little man told the story of his courtship, which had carried him through sea journeys and knife fights across the world. Indeed, he was Straight Sinewed of the Glen, a man without mercy and without fear of God or of man, with a mole on his forehead, a charmed shirt of yellow silk, a dart-resisting, flawless bright blue coat, a hero's sword and a cluster of narrow knives. He finally won his bride and took her home; she brought with her much gold and silver. "Is it a wonder, oh Murachag, that I do not care to have another man stare at her?. . . Then, although he was a famous hunter, Murachag Mac Brian shivered, and he made up his mind that never again would he stare at the wife of a woodman, however small. As far as I know he never has." As for loch monsters, there is caught here a three-headed one, the Uile-Beast. The means employed are apt, far more powerful than sonar and strobe light.

THE ANCIENT VISITORS, by Daniel Cohen. Doubleday & Company, Inc. ($5.95). The best-sellers of recent years include a variety of speculative works, the best-known surely being those of the Swiss hotelman Erich von Däniken, who wrote one of them while spending a year in jail for fraud. The crime had nothing to do with his books, yet it hardly serves as a character recommendation for one who intends to "show that all the experts are wrong." In this pleasant, timely book, an experienced science writer with a long-standing interest in the occult analyzes a large body of popular literature. The topics run from the Bermuda Triangle to Easter Island, from the huge markings in the Nazca desert to the crystal skull in the British Museum, from the Great Pyramid to Ezekiel's Wheel and the high-voltage Ark of the Covenant. Such disparate tales are brought together these days by a story that ascribes them, every one, to ancient visits of superior star folk.

The chief argument, when it is not based on overt distortion of the data, turns out to run more or less in the vein that those dull non-Europeans in Asia or Africa or the Americas could not possibly have made those grand and beautiful things. The stories are not in detail particularly new; Charles Hoy Fort had most of them before the Great Depression. But they persist. Cohen does a first-rate job of calm, skeptical analysis; "the fun of the book is in the evidence," he says. We ask big questions: questions of the universe, questions of the meaning and origin of life. We cannot get easy answers; the visitors with their UFO vehicles are too easy.

The young reader is left to make his own final judgment, but it is made pretty clear that the material is at best wildly unproved and at worst plain fake. Meanwhile Magnetic Hill is demonstrably not so magical, that Triangle does not eat planes and ships, and one would certainly like to see at least a snapshot of that boulder floating high in front of the mosque in Shivapur, the one that is supposed "to become weightless when eleven people stand around it touching it with their index fingers and chanting 'Qamar Ali Dervish' loudly." One welcomes this book, which is never hostile or condescending; libraries can make good use of it, and it may bring perspective to many readers.

ANCIENT INDIANS OF THE SOUTHWEST, by Alfred Tamarin and Shirley Glubok. Doubleday & Company, Inc. ($5.95). Don't lose the jacket of this book, because on the back of it is a photograph in color by Tamarin that captures the essence of Arizona's Canyon de Chelly. Far below the top of the towering red cliffs, yet safely above the green trees of the riverbank, a small masonry house is tucked into a silent sheltering crevice. In fewer than 100 pages the authors present an outline history of our Southwest from the coming of the first hunters pursuing elephants up to the settlement of the pueblo villages, when the mesa people at last came to dwell with those who lived by the rivers.

Those people live there still, in houses the color of earth among mountains that loom against the sky. In so few pages not much can be said about the people, but their places and their skills and their fate are named, and the plentiful black-and-white illustrations give a good sense of their wondrous arts and skills. A Clovis elephant spearpoint, a Mimbres rabbit bowl, an etched clamshell from the Hohokam at Snaketown, Montezuma's Castle and the great kiva at Chaco Canyon sample the photographs, most of them made by Tamarin. Any reader young or old who has seen these sites or read the museum labels and wants a compact but complete ordered narrative will find it here.

A LIFE OF THEIR OWN: AN INDIAN FAMILY IN LATIN AMERICA, text and photographs by Aylette Jenness and Lisa W. Kroeber. Drawings by Susan Votaw. Thomas Y. Crowell Company ($8.95). The family Hernandez look straight at you out of the frontispiece from their strong front door. Father and son are dignified, even grave; mother and both daughters smile cheerily. Two other young women, the American anthropologists who wrote the text of this unusually substantial book and made the photographs, are at the wrong end of the camera, but the book grows from the encounter between them and the Hernandez family. The Hernandezes live in the Indian village of San Antonio, not far from the old Guatemalan capital of Antigua. Mother and the 17-year-old daughter weave cloth to sell in the market, the beautiful hand-brocaded cloth the Indian women of this village have always woven. Father tills the small steep fields they own or rent for maize to eat and for chilis to sell in the city. Arnoldo, 12, and little Evelia go to school. First-grader Evelia plays with her doll or with her friends and sometimes buys an orange popsicle in the marketplace; Arnoldo plays soccer in the square.

The authors and the family met and became friends. Out of that all else flows. The tape recorder and the camera (the 200 photographs in the book were chosen from 4,000) were only tools, less important than honesty and care and the warmth that eventually came to surround the daily meetings, the sharing of meals, the strange questions and the awkwardness of the Spanish language that all used with some difficulty. (The northerners were of course more at home in English, the Guatemalans in their own Mayan tongue, Cakchiquel.) The first chapter of the book, which explains how such an anthropological study is carried out, is of itself a disarming and engaging tale of human diversity and human unity. It makes the book itself a believable enterprise, not something remote from the reader and everyday life.

The book goes on to let us see a little of the past of the village and its people, of daily chores, of the work of men and of women, of meals, school, health care, government, market, fiesta and church. There is a third part of the book: *taller,* a workshop, which tells how a group of children can come to "feel a little of what it's like to be an Indian in Latin America." There is a plan of the compound, and an outline of the way to carry loads and babies, to bathe, to plant chilis, to cook, to make kites, to go to market, to prepare for a carnival day. It is plain that this is not the life of many Americans: two marked differences are the steady physical labor, particularly for the women, and the unchanging diet. There are no schoolbooks, no television, no movies (there is radio); there are bicycles, buses and a doctor who comes once a week. Yet there are similarities that lie deeper; the world of San Antonio, like ours, is gripped by change. The task of the young there will be to hold a life of their own, with its traditions and its pride, while change works its will.

The earthquake early this year hit San Antonio heavily, but we do know that the Hernandez family has survived.

The Physical World

THE STARS BELONG TO EVERYONE: HOW TO ENJOY ASTRONOMY, by Helen Sawyer Hogg. Doubleday & Company, Inc. ($12.50). Professor Hogg is a

well-known professional astronomer at the University of Toronto; she patently enjoys her own work and has spent a long career working with the general public as well, writing a weekly newspaper column, lecturing and "poring over old books." It shows. She has assembled a fresh set of chapters on the sky, the real sky, with its surprises and disappointments, its joys and wonders, its depth and variety. In a few useful pages she gives us a "celestial log," a list of what you can see with your own two eyes: the atmosphere, the sun, the moon, planets, stars, star clusters and galaxies. Some things need "luck as well as persistence," such as a blue sun. She herself saw a mauve sun in 1950 in Toronto, during the great muskeg fires in Alberta that fall, whose smoke particles drifted across half of the world to induce dark days and remarkable color effects (which happen once in a blue moon!).

The chapters lightly pursue most of the familiar topics of popular astronomy, from eclipses and comets to constellations to pulsars and the large space telescope. They do not exhaust the reader or the topic; they open a door on the subject, as the telescope enlarges the astronomer's days and nights that she describes so honestly. The readable, personal, thoughtful text is most of the book; the illustrations are good but not showy, and there is valuable reference material. Any reader beyond the middle grades should profit from it.

COSMIC VIEW: THE UNIVERSE IN 40 JUMPS, by Kees Boeke. With an introduction by Arthur H. Compton. The John Day Company ($6.95). In its ninth impression this book, first published in 1957, remains a classic of science teaching. It begins with a photograph of a young girl sitting with a cat in her lap in front of the school near Utrecht where the late author taught. Then page by page we see careful drawings of what would come to our view as we pull back, examining each time a field one order of magnitude larger. Thus we withdraw to an airplane survey, a satellite map, a view of half of the earth and far beyond. We pass a sequence of dark, nearly empty scenes in the depths of space, until our galaxy fills the page in Plate 22. By Plate 26 we see a cosmos of galaxies like so many dust particles, our own galaxy quite lost among them.

The voyage begins again with the schoolgirl, but now we find a mosquito on her hand, in a view that has only a tenth the diameter of the original field. A few plates later we go beyond the microscope, to see a few viruses and the edge of a great salt crystal. We now enter an even smaller microworld, again passing through nearly empty fields, until at Plate Minus 13 we see the nucleus of a single sodium atom, drawn as a fuzzy gray disk.

The scrupulous accuracy of the plates is one feature of the work. Another is the genuine sense of voyage: nothing is shown to us that could not plausibly be there, and as far as knowledge goes everything is drawn as it is. For example, the planets are in the true positions of December 21, 1951, the adopted epoch. Today we could drive perhaps two orders of magnitude deeper into the nucleus and the nucleons, and we might include some sense of the supercluster of galaxies in Virgo, maybe even the primordial fireball of the big bang. But the spirit is changeless; the book has inspired any number of other authors and at least two admirable films animating and extending the cosmic view. Never before reviewed in these pages, the book foreshadows the wonderful photographs of the earth made from satellites, and it provides a seamless context for the innumerable images of micro- and macroreality we now see every day. It is an education in itself, as fresh as it ever was.

OPTICAL DESIGNS IN MOTION WITH MOIRÉ OVERLAYS, by Carol Belanger Grafton. Dover Publications, Inc. ($3). THE MAGIC MOVING PICTURE BOOK, by Bliss, Sands & Co. Dover Publications, Inc. ($1.75). These are two closely related bargains. Each is a thin book of designs in black and white, with a cover pocket that holds a piece of clear acetate printed with its own set of strong black patterns. When the transparent sheet is laid on one or another of the printed pages, moving it causes the striking effects we call moiré patterns to fill the eye. The effects are irresistible for viewers from six to 80; the only dexterity demanded is the ability to move the sheet quite slowly, a couple of seconds per centimeter.

The designs in the two books are quite different. *Optical Designs in Motion* presents some 80 op-art abstract patterns, with four different simple, open patterns on the overlay. It gives rise to a literally dizzying variety of optical twists and shimmers, occasionally even false color. The first page offers the self-patterns of the overlay, which are the most interesting for understanding as distinct from sheer dazzle. *The Magic Moving Picture Book* was a London novelty of the year 1898; it has a simple, close-ruled overlay and 15 engraved scenes, such as the Serpentine Dancer (parental guidance not required), the Traction Engine, the House on Fire. In each of these period scenes some specially ruled areas flash out in systematic shadowy motion. The direct experience is of real interest, and it can nurture a deeper analytic understanding later. The simplest ruled overlay placed on a ruled page of slightly different spacing (the Changeable Tint) exhibits the vernier, the root idea of interference and a valuable analogy with Fourier analysis. In *Optical Designs in Motion* radial and polar overlays display the effects of simulated two-source interference in simple cases, which are soon left far behind.

SOUNDS OF MUSIC, by Charles Taylor. British Broadcasting Corporation (£6.50). From the first picture of Professor Taylor sounding an oboe to the matched score and oscilloscope trace of the Mozart trio that is the final appendix, this volume plays out an up-to-date, highly informal introduction to the physics of music, copiously illustrated and free of formulas but by no means elementary. The book derives from the 142nd course of Christmas Lectures "for a juvenile auditory" at the Royal Institution of London (in 1971). Now that the BBC puts the lectures on television, they can be rich in visual aids, as these are. The skills of the University of Cardiff physics department, where the author teaches, and of Bill Coates of the Royal Institution and his laboratory are seen in the photographs and in much special apparatus.

The story begins with notations of all kinds, even the wonderful cartoons of Saul Steinberg. It passes soon to the idea of waves—something travels but not matter—and explicates the notions of frequency, patterns of periodic motion, modes of vibration and harmonics, with examples from Mendelssohn and the Pink Floyd, from thumb piano, siren, single string and saw. The next topic is transients: the bowing, plucking and striking that characterize real instruments. Then we see spectrum composition, illustrated with many examples, for instance noise pink and white, which we see generated by a 30-channel spectrum shaper and analyzed by a similar real-time analyzer. So armed, we examine the output of the instruments, from the Helmholtz resonator to the tenor trombone, for main components. Here the text faces up to the nonlinear effects that Professor A. H. Benade has so clearly identified as determining the sound of real clarinets and horns.

Speech is not forgotten, and its relation to the reed instruments is drawn on. The longest chapter treats in detail, if briefly, the acoustics behind the construction and design of brasses, woodwinds, fiddles old and new, keyboard instruments and the synthesizers and digital-analogue converters of today. A chapter on room acoustics makes good use of the waveforms visible in model rooms immersed in a ripple tank, and there is a final chapter on the ear.

We also learn about the judgment of pitch, the intensity of sound and speculations on the nature of musical scales. There is a useful column on talking drums, which helps to emphasize how little the ear is a mere telephone receiver and how much hearing is an active model-building process. This is not an easy book, but it is a fine start for a serious reader, and he needs little mathematics

for the task. Interested teenage students will find it enriching.

SIDEWALK FOSSILS, text and photographs by Robert Sommer and Harriet Becker. Walker and Company ($5.95). Dinosaurs left footprints by chance in mud that dried and once in a great while very slowly became rock. Such a track, looking like the print of a bird with foot-long claws, is neatly shown in this fresh book on seeing the world. Most of the other photographs offer prints of a related kind, again often accidental. Sidewalks are being poured in fresh moldable concrete just about every day, in season, in any city; in those surfaces you find the prints of people, pets, leaves, pinecones, badminton shuttlecocks and more deliberate souvenirs. These last include the trademarks of contractors, names (one is here in Chinese character) and figures telling us years later that *M* loves *Y*. Leaves are the commonest street fossils, but these clever California searchers even found a sundial. They tell about making rubbings of the impressions and how to make your own mark in your own little patch of concrete. There is a lot to figure out from this book, or from the sidewalk itself. Early readers can manage the book. (About all one misses is a remark on the possible ambiguity of viewing photographs showing relief: Is it concave or convex? Most of those here come right the first time.)

Technology

BUILD YOUR OWN WORKING ROBOT, by David L. Heiserman. Tab Books, Blue Ridge Summit, Pa. ($8.95). This is the real thing. The small, credible, detailed text, with lots of diagrams, logic tables and a few rather gray photographs, explains how to build Buster. He is no television-program robot with flashing eyes but a small self-operated device on wheels working "more like an animal than a machine." Buster's mechanical basis is a battery-operated toy automobile just large enough to carry a small child. Such a toy can be bought retail for $35 or less. Then your task is to fit it out with an evolving nervous system, amounting eventually to about 30 printed-circuit boards. The task is described in an evolutionary way, in three phases. In Phase I Buster becomes "an over-designed steering toy" able to follow push-button driving commands sent over a cable. In Phase II he develops the ability to run freely and to muddle his way out of corners and collisions, finally leaving the cable to obey acoustic commands. In Phase III—which is not at all the end of Buster's potential—he becomes able to follow his builder around the block or wander through the house for hours, and in the end he can find his way back to feed at the old home current trough.

This is no easy challenge. A lone part-time experimenter might take as much as five years to build and debug the boards with their hundreds of mostly discrete circuits (transistor-transistor logic), switches, relays, batteries and the like. The book is an intelligible plan and guide for readers with experience in printed circuitry, not a detailed recipe for rank beginners. It appears to be a first-class instructive task for groups or clubs of adept high school or technical school students; the author thanks the students and staff of the Ohio Institute of Technology at Columbus. (Please do not write these inexpert reviewers if some bug infests a diagram. Try the author!)

BOOMERANGS: MAKING AND THROWING THEM, by Herb A. Smith. Illustrations by Malcolm Kemp. Photography by James Clevett. Gemstar Publications, Littlehampton, Sussex, England (£0.80). Smith makes and throws returning boomerangs superbly well (his record is 108 yards out and back to the mark) even though "like the aborigine, bless him, [he is] blissfully ignorant of the reasons a boomerang will perform in a certain way." Trial and error has led him (and them) to a certain mastery. He shares it in this booklet, which tells how to make a boomerang, decorate it, throw it and catch it. Two very simple boomerangs are described as a bonus: one made of two rulers and the other of cardboard. The final chapter tells how to make distance throws for return. (The secret is a ballast of lead.) It is important to recognize that the Australian hunting boomerang was made as an accurate missile for small game, which it could stop over a range of up to 150 yards. It did not return, and it was not meant to. The return boomerang of the aborigines was much lighter than their hunting weapon; it was made and used for its own sake, often in competition. The two types are confused in many conventional accounts. Australian boomerangs have a return range of perhaps 40 yards, but of course they have no lead ballast. For the theory of the boomerang there is still no better source than the article by Felix Hess of the University of Groningen in *Scientific American* for November, 1968.

THE UNDERWATER DIG: AN INTRODUCTION TO MARINE ARCHAEOLOGY, by Robert F. Marx. Henry Z. Walck, Inc. ($9.95). Archaeology is an addiction, and Robert F. Marx has it. Once an underwater adventurer, a mere treasure hunter, he has dived onto 500 shipwrecks (including two ships of Christopher Columbus!). Now he is caught all the way: he offers drawings of types of glass bottles and olive jars decade by decade, a similar set of sketches of clay smoking-pipe patterns, the types of cannon to be found on Spanish ships by date, coins and their literature, and how to get expert advice on bones and buttons, ballast and boulders. He found the second-richest ship to sink in the Western Hemisphere, the *Maravilla*. He dived onto her in the summer of 1972, only half a mile south of where his chart said she lay. He got that chart not from some old salt who traded it for rum in a Caribbean bar but after "culling more than twelve thousand pages of documents" concerning the ship in the famous and dusty Archivo General de las Indias in Seville. He is now digging earthquake-submerged Port Royal in Jamaica, where archives can often identify the house he is working in by the name of the owner.

This personal volume is an invitation to involvement. It is meant for the amateur who wants to dive into the past. There are three million scuba divers in the U.S. and a million in Europe. They have done far more harm than good to our knowledge of the past; they have opened wrecks and submarine deposits not for the unique story they can tell but for metal scrap or souvenirs. Once the object is gone its story remains untold; sometimes the act removes the one trace by which a wreck can easily be found. The book sets the stage, treating the research above the water, the search for the site itself, the excavation, the problems of identification and dating, of preservation and publication; it also provides a glimpse of the future. Through it all is the enthusiasm and experience of the amateur par excellence who turned real pro.

Here are the Hookah and Desco diving gear, and the Surface Air Supply system, the cheapest and safest way to work in shallow water. Here are the airlift and the prop-wash tube, Loran and side-scan sonar, no less than the diver's personal marker buoy, made of painted balsa about the size of a six-inch length of broom handle. The book is never as systematic as a how-to-do-it, but it is full of knowing hints and experienced appraisals of how to solve the endless problems of the underwater dig.

So far we have been only coastwise archaeologists, but in the true depths of the sea there lie intact, undespoiled wrecks in vast numbers, their wood preserved, far below oxygen and free of shipworms and coral, beyond the reach of storms and careless divers. There "the richest museum of antiquities in the world" remains to be opened.

THE PENGUIN BOOK OF KITES, by David Pelham. Penguin Books ($4.95). Pelham is a longtime kite freak who has spent the past eight years as the art director of Penguin Books. This attractive book, which combines his interests, is divided neatly into sections. In the first section the kite is examined in history. After the ancient days the author focuses on the 19th century and later, with a

good deal to say about the modern delta wings, flexibles and parafoils. The figures are numerous, from the kite-borne escape of a noble Japanese captive (after a print by Hokusai) to the industrial parafoils of today, hauling logs or lifting aerials. The next section brings a collection of color photographs, half of them brilliant modern structures and half marvelous traditional forms from China and Japan. The last section is devoted to the construction of kites. Half of the book is given over to large sketches, black and white on brightly colored pages, with construction hints for knots, joints, cloth, reels, bridles and tails. Hints on where and how to fly are not omitted.

That part of the book shows in outline form some 100 patterns of kite, all reportedly flight-tested, ranging from the complex and difficult to mere folded writing paper. (There are a few bits of British jargon, for example "A4 paper.") These diagrams are clear, but they are not step-by-step recipes; they ask for a little experience or at least some handy know-how. It is a fine book for those with enterprise but not for sheer beginners at reading or at kites.

Language and Form

AN INTRODUCTION TO TENSEGRITY, by Anthony Pugh. University of California Press ($4.95). GEODESIC MATH AND HOW TO USE IT, by Hugh Kenner. University of California Press ($5.95). It was that human verb Buckminster Fuller, "instigator nonpareil," who found the thing and its name: tensegrity. (The name is from tensional integrity.) It need not be made, although the most familiar ones certainly are, of stiff struts and taut tendons. The wonder is that "the struts of the figures do not touch one another, but appear to hang within the tendons as if by magic." There is no magic: Newton's equilibria are here, the elastic energy high, the equilibrium stable but tensely vibrating. These two books are quite different in level and approach; together they present an explicit rationale and a process of systematic introduction that lead both to intuitive power and considerable calculational control over the design of complex model structures, and to the fundamental, rather than the practical, design of domes. Indeed, the Kenner book, primarily analytic and computational—with programs for the Hewlett-Packard HP-65—derives the very nature of a geodesic dome quite convincingly as the limiting case of a more complex skin of simple tensegrities. Pugh aims at helping the reader to stretch himself to the design of models all the way from desktop scale to man-sized masts and domes, as a path to understanding but without much analysis.

The Kenner book is split into two parts. The first explains and derives the mechanics of simple tensegrity figures from "a tent without a center pole" and relates them eventually to the rigid dome. The second is a geometry of the geodesic dome in high generality, going even beyond spheres, with plenty of calculational aids. Its readers should know algebra and a little high school trigonometry and feel at home with the keyboard of some pocket calculator. Either book will in its way open wide a new gate to a familiar, faintly mysterious part of the world of structure; they should attract student and hobbyist groups in droves.

Anthony Pugh is a professional designer but Hugh Kenner is a gifted amateur. He is professor of English at Johns Hopkins, no mathematician or engineer at all, a living tribute to the unity of human wit and mind.

THIRTEEN, by Remy Charlip and Jerry Joyner. Parents' Magazine Press ($5.50). Thirteen pictorial spreads meet the reader's eye as he turns these pages. Each spread displays a big black number—in countdown order—and 13 glowing miniature watercolors, some with captions, in bewildering variety and with no evident meaning. Then illumination strikes: each position in the spread holds a picture that is one of a sequence unfolding spread after spread its fascinating little narrative. Thirteen tales run side by side, from the galleon that sinks in a bottle sea to the surprising find of a plump and powerful Cinderella, to a mysterious pyramid that is part of a hierarchical universe, to unfolding paper acrobats who balance on the point of a needle, to a day's weather, to.... These are for the most part transformations of meaning and scale, into and beyond space and time, each with a surprising, often whimsical but indubitable logic of its own. Across the opening endpaper falls a russet dead autumn leaf. On each pair of pages another plausible marvel happens to that leaf, and out of the closing endpapers floats a russet leaf butterfly, brilliantly alive. This book is beautiful, ingenious, puzzling, witty and without parallel for anyone who can sit still to consider what he sees.

THE COMPLEAT COMPUTER, by Dennie L. van Tassel. Science Research Associates, Inc. ($5.95). Ten color reproductions of covers of science-fiction magazines are included in this large-paged floppy paperback anthology. With them are poems, computer graphics, cartoon strips and 100-odd serious comments from technical and popular sources. Altogether the book is an experience of acculturation; it leads the reader, young or old, into the subculture dominated by tape and keyboard, with both the boasts and the serious worries about what they will mean to us all. Here are the true classical pieces: A. M. Turing's imitation game, Arthur C. Clarke's magnificent brief story *The Nine Billion Names of God,* and the touching passage on the lobotomy of the mad computer HAL. (If you haven't met him in the book, you have in *2001.*) There are the obligatory photographs of Pascal's calculator and Babbage's engine, and pieces from way back in the 1950's up to the great Cal Tech caper of 1975, which flooded a McDonald's contest with a million computer-printed entries and won most of the prizes. There are W. H. Auden and Norbert Wiener. There is a funny series of *Doonesbury* comic strips in which poor Mark, misled by a book of paper matches, fails to earn a summer's living working at a PDP-112 terminal, a dourly honest man fallen among true believers.

The pieces are staccato, and many are heavily cut, without any marks of elision. Otherwise the book is, as it says of itself, fun and beautiful; perhaps readers from grade school up can find in it a first step to greater depth. One or two cartoons (among many) appeared tasteless to these reviewers.

GETTING STARTED IN PRINTS AND PATTERNS, by Stanley Rice. The Bruce Publishing Company, Collier-Macmillan Limited ($2.95). FANTASY & SYMMETRY: THE PERIODIC DRAWINGS OF M. C. ESCHER, by Caroline H. MacGillavry. Harry N. Abrams, Inc., Publishers ($15). These are two studies in plane pattern, each done by an artist, each pointing beyond art to the theory of groups. Rice is a printmaker and college art instructor who offers an account of methods, techniques, materials and examples for surface-pattern design. The instructions are simple and practical, mostly for printing with a rubber stamp or a potato, and the examples are engaging. The entire work is suffused with such a lively sense of what repetitive pattern is, both in nature and in art, and big mathematical truths are so naturally invoked, so free from all notation or jargon, that the book must be counted just as much introductory science as it is introductory craft. The single page that shows a snowflake, a computer pattern on a cathode-ray tube, a printed circuit, a Mississippi meander, a chunk of fossiliferous rock and a rug at the Metropolitan is worthy of any text on microphysics. The book will work for children from eight or so on up.

The MacGillavry book, a reissue of a 1965 publication (which then bore a less attractive title), is a gloss by an Amsterdam crystallographer on some 30 black-and-white and a dozen color plates that present witty and enigmatic figure-ground drawings by the famous Dutch artist. Professor MacGillavry takes each plane of mingled birds and fish or joined angels and devils and in a page or two points out key symmetry elements, probable unit cells, planes of symmetry, the glide lines and axes of rotation. In

this way she builds up the full plane symmetry of each pattern, with some broader color symmetry. She too is no artless pedagogue; she cleverly gives only the main lines of the arguments. The reader is thus left with his own problems, which lead him to a deeper and self-testing understanding of the symmetries of the plane. The book is explicitly mathematical, all right; it has a glossary, but it uses the difficult notation of that field. It is a natural treasure for mathematics libraries at the teenage level and beyond, and a temptation to anyone who enjoys the theory of groups.

BIG AND LITTLE, by J. P. Miller. Random House, Inc. ($2.50). BIG ONES, LITTLE ONES, by Tana Hoban. Greenwillow Books, William Morrow & Company, Inc. ($5.95). MEASURING THINGS, by Iris Grender. Designed and illustrated by Geoffrey Butcher. Pinwheel Books, Knopf/Pantheon ($1.25). Three very different little books for the pre-reader center on the theme of size. *Big and Little* is a set of five heavy cardboard leaves bound between two more of the same. They have rounded corners and bear bright, strong pictures on a glossy paper surface; the book will withstand determined efforts to eat it. We see a tall crane and a short duck, a fat bullfrog and a thin one, a few yellow chicks and many, a cat jumping over mice under a chair, and the like. The attention shifts more to language, to opposites, than the size theme of the title suggests, but the book is a well-done example of a time-honored form.

Big Ones, Little Ones is a piece of black-and-white photographic naturalism. We find a polar bear and its cub, an elephant and its new offspring, a zebu and its calf, a pig and a piglet, a peahen and a peachick, and more, all clearly and evocatively photographed by this well-known artist of the camera. There are no words except for the labels on the final index page, which carries a thumbnail-sized version of each of the big full-page photographs. The images evoke not only size contrast but also nurturance.

Measuring Things is an English book of an interesting new series that offers at a low price a set of die-cut pages that can be punched out to make a number of stiff paper games and toys. This one includes "twelve easy games to introduce children to weights and measures," a rather heavy description of light matters. One folded page covers up long intertwined leashes to make it look as though each child is holding the nearest dog on a short leash, another shows a series of concentric colored rings that come out as a set of gauges for an arm or a drinking glass or simply as a size-sorting game, a third is a set of clock dials without hands, with a drawing beside each of a child at breakfast, watching television and so on as clues to putting the hands in properly. The original publisher was called Three Four Five Publishing Ltd, which names the audience. These are agreeable booklets.

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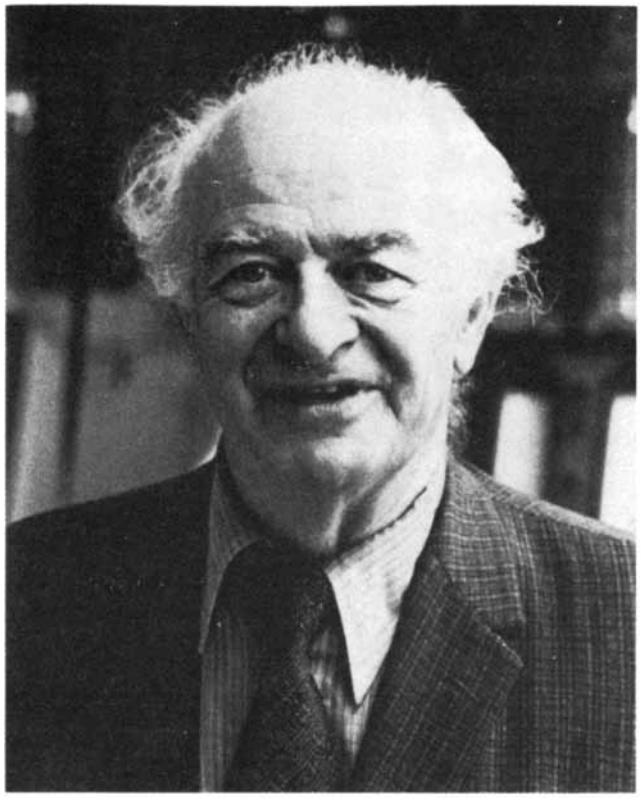

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