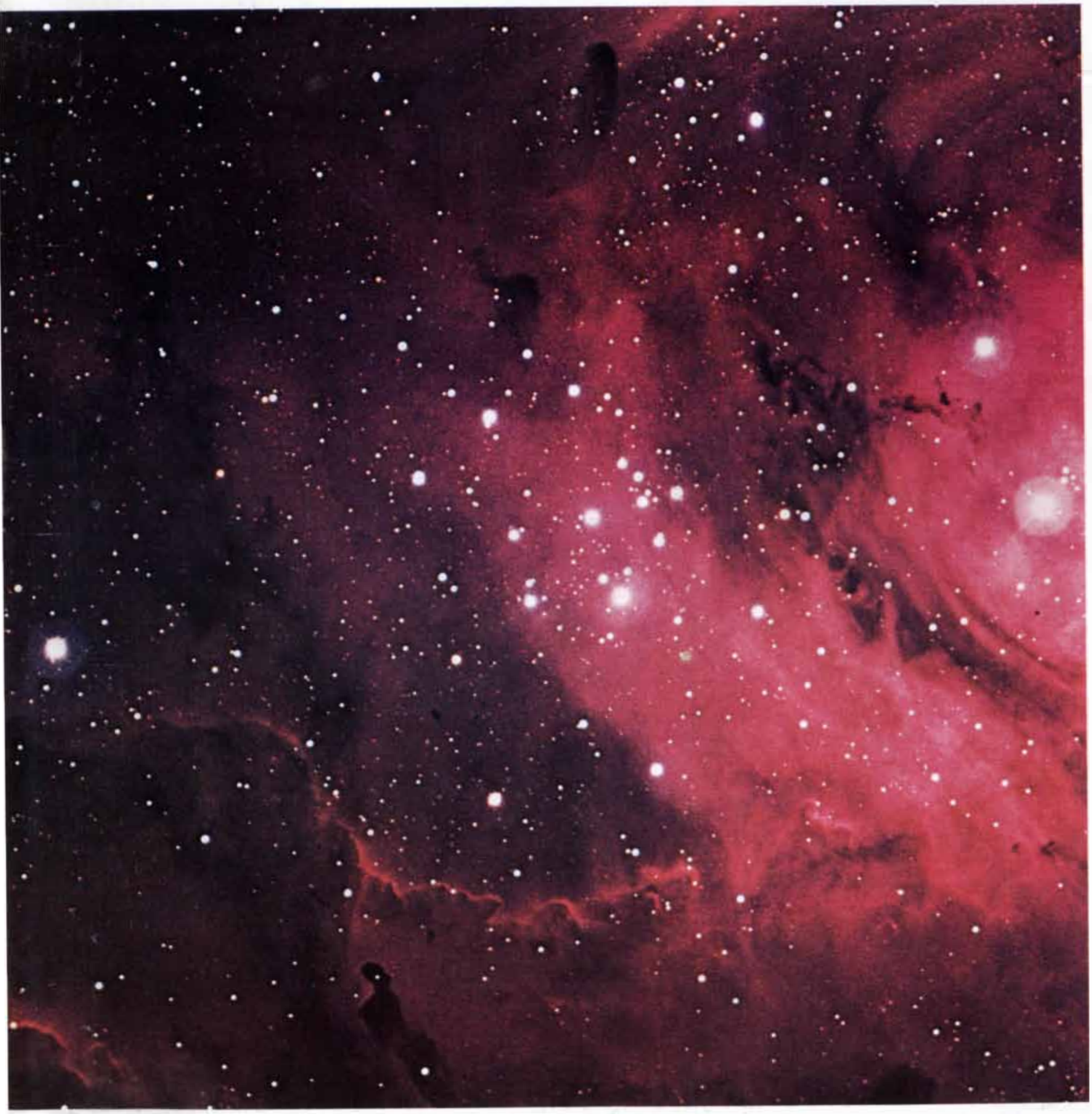
SCIENTIFIC AMERICAN



STARS IN THE MAKING

$1.50

June 1977

Diplomat 2-door base price	$4943.00
Diplomat Medallion 2-door (shown) base price	$5313.00
Optional equipment	
Landau vinyl roof	131.60
Wire wheel covers	34.65
Whitewall tires	42.85
Total price of Diplomat Medallion as shown	**$5522.10***

*Manufacturer's suggested retail price including options shown above. Taxes, destination charges, title, and additional equipment are extra.

Optional leather and vinyl interior $208 extra (available on Medallion models only).

Established 1845 **SCIENTIFIC AMERICAN** June 1977 Volume 236 Number 6

ARTICLES

DEPARTMENTS

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executive health

the report that briefs you on what to watch

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Case Histories . . . Part III

On how to LIVE 90 to 100 HEALTHY years

(The syndrome of longevity . . . its 7 great "constants")

"There is no short-cut to longevity. To win it is the work of a lifetime . . ."
—Sir James Crichton-Browne (1840-1938)
in his *"The Prevention of Senility"*

The errors of our younger years are drafts upon our older years, payable (with interest) some 30 years from date.

The so-called "diseases of old age" are essentially the diseases of 50 to 70 . . . *"the dangerous years!"*

Research scientists have observed that people who survive these "dangerous years" *successfully* (without acquiring some "chronic" disease such as cancer or heart trouble) are likely to live on for another *healthy* quarter of a century. They seem to have developed what might almost be called an *immunity* to these killers. Why?

To try to find out, some careful studies have now been made of these *extraordinarily* long-lived individuals.

What do these show? Is it what you might expect . . . just a matter of sheer chance . . . *amazing luck?*

Luck plays a part, of course. (This world is a dangerous place. It always has been and, probably, it always will be!) But these studies show that other factors (not at all dependent on chance) seem *dependably* present . . . "constants." As you study the *case histories* of these extraordinarily long-lived individuals, 7 of these great *"constants"* almost invariably turn up! They form what is now becoming known as the *syndrome of longevity.*

As an executive, your safest guide (as to what you should do, or not do, to live a long, long time *in good health*) is to study, and try to apply to your own life, these 7 great "constants" so evident in the lives of other executives who have outlived their contemporaries *by a generation.*

Nearly four years ago in *Executive Health* (Vol. III, Nos. 5 and 6) we gave you some detailed *case histories* of distinguished men whose lives sharply emphasized the

THE COVER

The photograph on the cover, made with the 150-inch reflecting telescope of the Kitt Peak National Observatory, shows part of the Lagoon Nebula in the constellation Sagittarius. The nebula consists of gas and dust. Some of the gas is luminous because its atoms are excited by ultraviolet radiation from hot young stars embedded in it. Some of the dust is visible as dark clouds because it blocks the light of the luminous gas and stars behind it. Among the dark clouds are numerous small round objects known as Bok globules (for the astronomer Bart J. Bok). Globules may well be clouds of gas and dust in the process of collapsing to form stars (see "Bok Globules," by Robert L. Dickman, page 66). A typical small Bok globule is the dark speck, about the size of a small star image, half an inch below the bright star at the far right. The halo and cross around the brightest stars in the photograph are artifacts of telescope optics.

THE ILLUSTRATIONS

Cover photograph courtesy of Kitt Peak National Observatory

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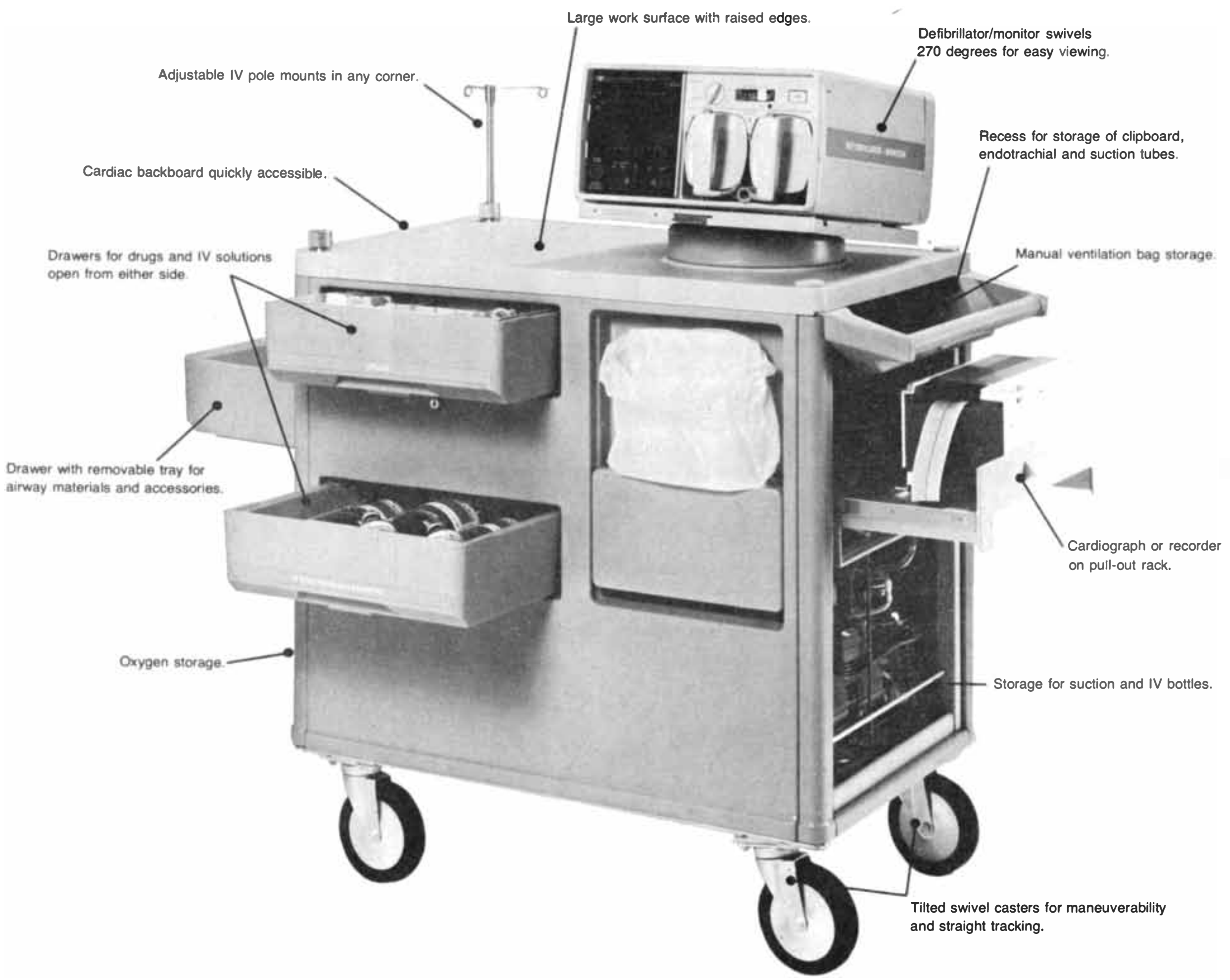


New resuscitation system speeds emergency aid in hospitals.

In one compact cart, HP's resuscitation system carries everything a medical team needs for 30 minutes of patient support including battery-operated defibrillator/monitor; recorder; organized storage for all drugs, equipment, and supplies—ready for immediate use on arrival at bedside.

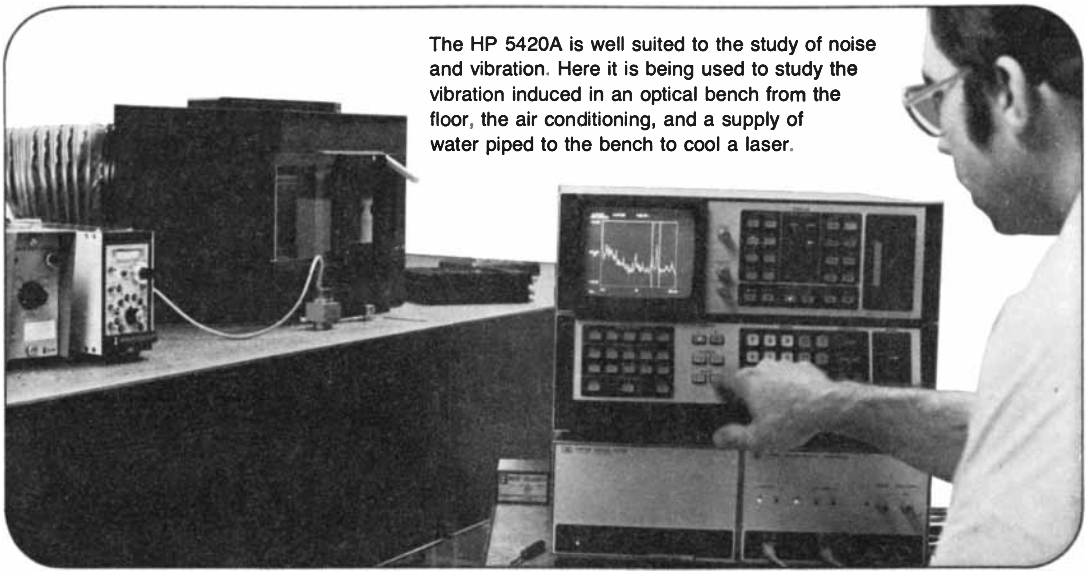
Speed. That's the essential meaning of the sound of an emergency code in a hospital. Never is the need more critical than when a medical team responds to a resuscitation code, because a minute or two can literally mean the difference between life and death.

It is precisely this matter of life and death that prompted us to re-examine the resuscitation team's instrument needs. The result is a new resuscitation system, aimed exclusively at helping the medical team reach its first objective: to arrive at the emergency bedside quickly, with everything it needs ready for use.

Essential to the system is the new cart illustrated above. It provides organized storage space for all the medical team's needs, and is easy to maneuver in crowded corridors and tight spaces. It is designed to allow full access to system instruments and supplies: two-way drawers open from either side, and the top of the cart, except for the swivel-mounted defibrillator/monitor, remains clear for use as a work surface.

Many innovative features of the new defibrillator/monitor let the medical team concentrate on the quick application of emergency procedures without interruption for instrument adjustments. Thus the instrument is automatically set for defibrillation when power is turned on; the defibrillation paddles are instantly accessible, and serve as ECG electrodes for immediate initial cardiac assessment; charge and discharge buttons are built into the paddles; an internal battery delivers one hundred 400-joule discharges or seven hours of continuous monitoring on a single charge, and its built-in charger permits instant AC back-up; ECG waveform size and position are automatically adjusted on the scope and, after defibrillation, the trace automatically returns to non-fade display.

The new resuscitation system is available in a choice of eight models, to suit individual hospital needs without compromise. System prices start at $5600*.



The HP 5420A is well suited to the study of noise and vibration. Here it is being used to study the vibration induced in an optical bench from the floor, the air conditioning, and a supply of water piped to the bench to cool a laser.

How to use powerful analysis techniques on complex analog signals without being an expert.

Once restricted to those versed in the complexities of Fourier transform mathematics, the time and frequency domain analysis of low frequency dynamic signals can now be made by people with far less understanding of the mathematical theory, and with far less attention to instrument set-up details.

The intelligence built into HP's new 5420A dual-channel digital signal analyzer literally guides the novice to the desired result. The instrument's CRT displays the "menu" of measurements from which to choose, then shows the appropriate instrument setups for the choice you have made, and finally sets forth the measurement results. An integral tape cartridge stores both measurement data and instrument set-up state; to repeat an analysis you need press only two keys.

Measurement versatility is inherent in the HP 5420A. Basic frequency domain measurements it can make include linear spectrum, auto power spectrum, power spectral density or energy density, cross power spectrum, high resolution auto spectrum, transfer function and coherence. In the time domain, the HP 5420A measures time average, auto-correlation, cross correlation, and impulse response.

The analyzer's user-interactive display cursors let you read out any values along a signal or expand both the X and Y axes about an area of interest. Moreover, the instrument also offers a 75 dB dynamic range and "zoom" capability, providing a frequency resolution of up to 0.004 Hz anywhere in the 25 kHz bandwidth.

With the HP 5420A, you can post-process measurement results using the four basic arithmetic functions as well as integration and differentiation of complex data. Thus, for example, you can determine the coherent output power from a device by measuring the coherence function on one trace and total power on the other, and multiplying the two together—all with simple keystrokes.

The HP 5420A's applications are wide ranging—from structural and vibrational analysis to analysis of underwater sound or electronic circuits. At $29,900*, it is a very cost-effective tool for digital signal analysis of complex analog signals.

HEWLETT hp PACKARD

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Please send me further information on

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( ) HP 5420A digital signal analyzer

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*Domestic U.S. prices only.

00745

LETTERS

Sirs:

I found much food for thought in Kosta Tsipis' article "Cruise Missiles" [SCIENTIFIC AMERICAN, February]. I agree with most of the discussion and with the majority of his conclusions, particularly those regarding the promise of tactical, non-nuclear armed cruise missiles for replacing vulnerable and costly manned fighter-bombers. But with the degree of cooperation required for Tsipis' satellite-verification scheme to be effective (cruise-missile testing in the absence of cloud cover, certain design constraints regarding infrared signature and the like) I think a much better verification system could be devised that would require only a similar amount of cooperation. This would involve:

1. Testing on coastal ranges only.
2. Preannouncement of tests.
3. Announcement of the type number of the missile under test.

Of course, whether an agreement is verifiable depends not only on the means of verification but also on the nature of the agreement. Cruise missiles need not derail the SALT process.

RICHARD L. GARWIN

Thomas J. Watson Research Center
Yorktown Heights, N.Y.

Sirs:

In his article "The Reprocessing of Nuclear Fuels" [SCIENTIFIC AMERICAN, December, 1976] William P. Bebbington describes the waste products from coal as "essentially worthless and innocuous ash." On the basis of my experience with disposal problems associated with ash and sulfur sludge from coal-fired power plants I would disagree.

Fly ash from a power plant is alkaline and can contain hazardous trace metals, depending on the type of coal burned. Bottom ash may be alkaline or acidic, depending on the sulfur content of the coal burned. Pyrites removed from the coal during crushing are a highly acidic waste. Air-quality regulations issued pursuant to the Clean Air Act that limit sulfur dioxide emissions have given rise to a new waste-disposal product: sulfur dioxide scrubber sludge. Unless the sludge, a toothpastelike sulfur compound, is stabilized it doubles the quantity of waste and can represent a large commitment of unusable land over the life of a coal-fired plant. Since the waste products of coal plants are not "innocuous," they must be disposed of in a way that will not pollute the ground or surface waters or spoil the terrestrial environment.

Over the life of a coal-fired plant the waste materials from a 1,000-megawatt plant may fill one to two square miles of land 30 to 100 feet deep with waste. Currently 50 to 60 million tons of coal ash is produced in the U.S. annually; projections double this by 1985. Such a major commitment of land resources should be made with a full recognition of what is involved.

Since disposal may present problems, there are alternatives that should be considered. Ash has considerable potential as a construction material, as structural fill, in blocks and bricks and in cement. It is not "essentially worthless." The logistics of introducing ash into our economy, however, remain to be perfected. Power plants are not always sited at locations convenient to construction or other activities that might utilize ash. A network of supply and distribution links will have to be developed before ash can be introduced on a major scale into the economy. At present only about 10 percent of the available ash generated in the U.S. is used for some purpose.

Ash disposal tends to be neglected in the primary analysis of the impacts of coal-fired power plants that have too frequently led to air, water and land pollution later. With the advent of very large coal facilities and tough environmental laws the issue of how ash and the by-products of flue-gas desulfurization are to be disposed of will have to be

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5 IMPORTANT REASONS FOR CHOOSING AN ALFA ROMEO

VERSUS A BMW OR PORSCHE

	1. All Aluminum Engine	2. Double Overhead Cams	3. DeDion Rear Suspension System	4. 4-Wheel Power Disc Brakes	5. 5-Speed Transmission
Alfa Romeo GT	**YES**	**YES**	**YES**	**YES**	**YES**
BMW 320i	NO	NO	NO	NO	NO
Porsche 924	NO	NO	NO	NO	NO

Alfa Romeo Sprint Veloce

There are in the world some very beautiful versions of the personal motor car. You know the names, and the look. When you see one on the road, you notice it.

But you can't really know these cars until you know what's inside them. What's inside an Alfa is the result of 67 years of world class racing competition. (Alfa won its first Grand Prix in 1925. And its latest world championship in 1975.)

The comparison chart above lists five Alfa features; they are major car components, not superficial distinctions. None of these features is found in BMW (320i) or Porsche (924).

The all-aluminum engine for instance. Only four other cars have it. Rolls Royce, Jaguar, Ferrari, Maserati. At two to five times Alfa's price.

The DeDion independent rear suspension. Only one other car available in the U.S. has it—the $40,000 Aston-Martin.

By combining these two costly major advances, Alfa created the world's first truly balanced production car. Half the weight is in the front, half in back. The result is precise handling, easy steering, sure-footed roadholding.

There are other important differences inside an Alfa. Disc brakes on all four wheels instead of just the front two. Five-speed transmission for the important economies of an overdrive.

With all these advantages, you'd expect an Alfa Romeo to cost more than a BMW or a Porsche. Several years ago, it did. But then came the devalued lira.

Surprising prices

Since 1972, in the U.S., the dollar has grown 49% in buying power compared to the Italian lira. In that same period, the dollar has lost 27% in buying power compared to the German mark.

That is why, in the U.S., Alfa Romeo simply has not gone up in price the way German (and American) cars have. In fact, you can now buy an Alfa Romeo for less than comparable BMW or Porsche models.

See an Alfa, inside and out. It's a unique experience.

5 engineering achievements in Alfa Romeo, bred in 67 years of world class racing competition

1. All-Aluminum Engine. Its light weight makes possible better weight distribution for surer control. And, of course, its lighter weight is a gas-saver.

2. Double Overhead Camshafts. With this advanced feature, the Alfa is also economical to run. It gives you excellent gas mileage you might not expect in a high performance car.*

3. DeDion Independent Rear Suspension. It made possible a whole new driving experience—uncanny handling and roadholding abilities that conventional systems simply cannot match.

4. Four-Wheel Power Disc Brakes. Your Alfa stops faster—and without swerving or fading. Demonstrably superior to BMW and Porsche, according to Road & Track's January 1977 issue.

5. Five-Speed Transmission. It is synchronized for smooth, effortless shifting. The fifth is an overdrive gear for maintaining high speeds at low engine rpm's—resulting in exceptional gas economy and longer engine life.

EPA mileage ratings: The GT and Sedan models rated 19 mpg-city and 25 mpg-highway (21-city and 32-highway in California). The Spider model rated 18 mpg-city and 25 mpg-highway (19-city and 27-highway in California). These are only estimates. The actual mileage you get will vary depending upon the type of driving you do, driving conditions, your driving habits, and your car's condition and optional equipment.

Alfa Romeo Sports Sedan

Alfa Romeo

Alfa Romeo Spider Veloce

addressed in a more sophisticated manner than it has been in the past.

WILLIAM D. LILLEY

Consulting geologist
Elsmere, N.Y.

Sirs:

In "The Origin of Atherosclerosis," by Earl P. Benditt [SCIENTIFIC AMERICAN, February], there was a graph that showed the death rate from cancer of the colon compared with the death rate from arteriosclerotic heart disease for various countries.

The two were correlated, but what I find striking is that all the countries at the top right-hand side of the graph are English-speaking whereas none of the countries to the center and lower left are English-speaking. Although I do not wish to suggest that speaking English is dangerous to one's health, there must surely be some factor at work that is not a function of the degree of development or industrialization of the country. Perhaps it has to do with food intake, but even that is hard to believe.

The division between these two classes of countries seems to be too striking to be a coincidence. Can anyone suggest what the cause might be? If not, perhaps people should be warned against the risks of speaking English!

GERRIT L. VERSCHUUR

University of Colorado
Boulder

Sirs:

I write concerning the engraving of a running horse that was derived from the photographs by Eadweard Muybridge ["A Horse's Motion Scientifically Determined," SCIENTIFIC AMERICAN, October 19, 1878, and "The Control of Walking," by Keir Pearson, SCIENTIFIC AMERICAN, December, 1976]. The positions of the front legs as shown in Frame No. 9 should be reversed if they are to be consistent with the explanation of flexion-extension. The engraving of Frame No. 9 shows the horse's right rear leg and right front leg in a later stage of the swing phase while the left rear and left front legs are in the beginning stages of the swing phase.

It is my contention that the error was due to the engraver's misinterpretation of the photographs. Considering a shutter speed of a five-hundredth of a second and the state of photography in 1872, I imagine that the prints he had to work from were little more than shadows.

MICHAEL CRAGGS

Granite Falls, Wash.

Distinguished for the quality of service it provides and distinctively marked by the engine that sweeps cleanly through the tail, our DC-10 is the crowning achievement of 40 years of continuous airliner production.

So widely used, and useable, it now flies to more places, more often, than any other wide-cabin jet.

Airlines like the remarkable reliability and unmatched fuel efficiency of the DC-10. Passengers—more than 100,000 each day—appreciate its smooth flight, wide seats, big windows, high ceilings, attractive lighting and the uncommon quiet of the cabin.

DC-10s serve 150 cities on six continents. Take one on your next trip. You'll be pleased—and so will we.

Building jetliners and spacecraft and fighter planes occupies much of our time, but it also creates a healthy climate for creativity that can yield surprising results. For example, the space age technology that insulated and contained liquid hydrogen on Saturn moon rockets is now being applied in an improved method for ocean shipment of super-cold liquid natural gas (LNG). The insulation being produced by our Astronautics Company provides added safety for shipment of the fuel, offers increased cargo loads for existing ship designs, or permits greater capacity in new small ships. We can't do it alone. Our insulation material must be joined with a metal barrier designed by Gaz-Transport of France, and of course, a ship to carry it. But if you have tankers, or build them, ask us about insulation. We'll know what you mean.

Our engineers, once concerned with the health of astronauts, were encouraged to turn their wits to broader problems of health care. The result—an automatic system for identifying infectious organisms in patient samples, such as urine. The system also identifies, for attending physicians, the antibiotics most likely to counter the malady.

This AutoMicrobic™ System, designed and built by McDonnell Douglas and marketed by Fisher Scientific, eliminates

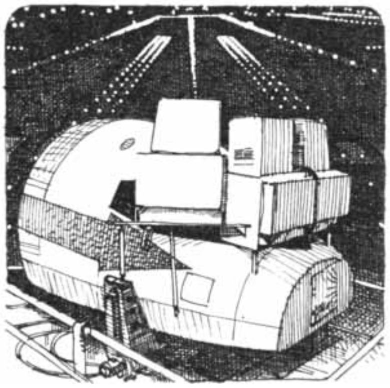
You'd expect McDonnell Douglas to build the reliable and popular DC-10...

...but would you expect us to keep natural gas super-cold, help train pilots and make electricity from the sun?

many repetitive tasks now performed manually, freeing technicians for more useful work.

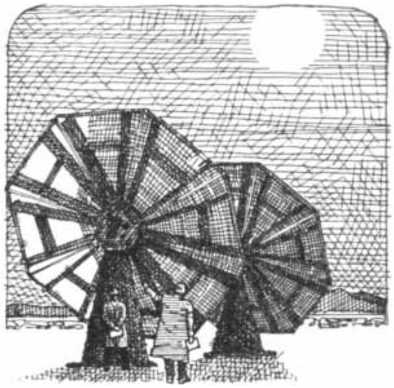
The disposable test kits that receive the patient samples for analysis are filled with growth-stimulating nutrients. Growth in these kits is automatically monitored and results are displayed to hospital personnel and printed out as reports. Now being sold for organism identification, the system is awaiting FDA approval of its antibiotic mode.

Fuel conservation is becoming a necessity to airlines with soaring fuel costs. Our Electronics division uses digital computers to create scenes through the windshield for pilot training simulators. They're so realistic that Federal regulators



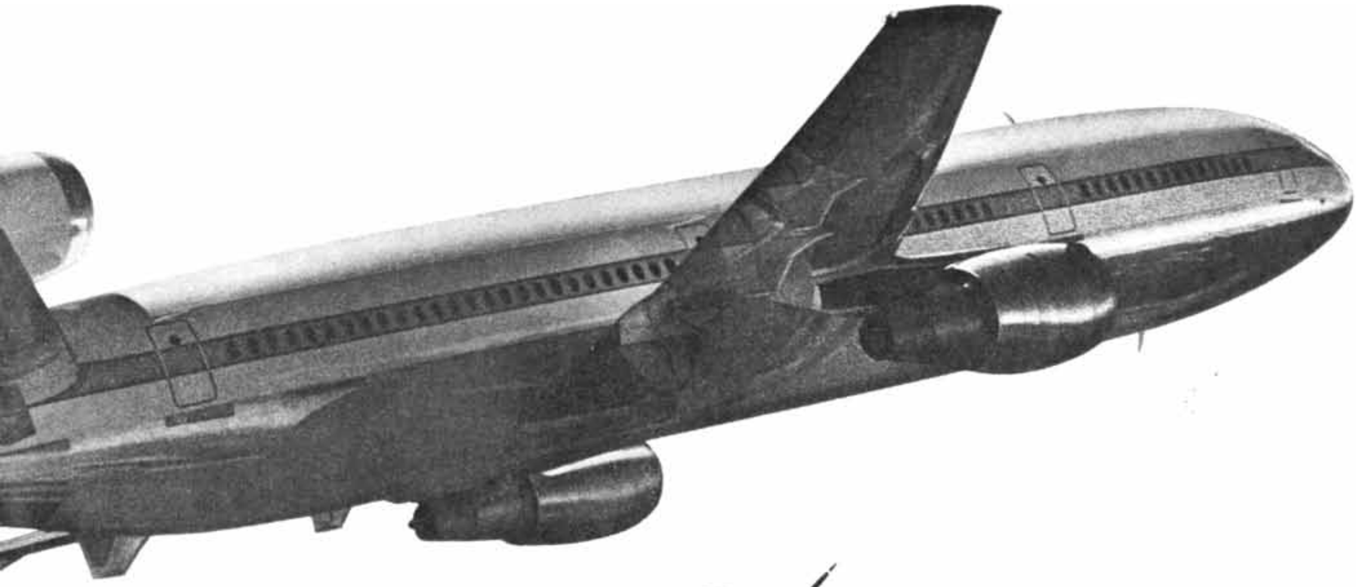
now permit ground training for a dozen pilot training maneuvers that once required costly training flights. One airline, using several of our VITAL systems, claims fuel savings of 4 million gallons a year. Systems are now being introduced for military pilots to let them train for formation flying, carrier landings, air refuelling, even for combat, all without leaving the ground. Money is saved, time is saved, and safety is enhanced. Early units permitted night training only. Daylight systems are now being demonstrated. For those who are pilots, or who train pilots, it's amazing. For the rest of us, the fuel saved is a godsend.

Speaking of godsends, we call your attention to a government agency really immersed in the energy problem. The Energy Research and Development Agency has us developing mirrors that track the sun, focusing rays onto a tower-mounted boiler to produce super-heated steam. The steam passes through a conventional turbine—presto—electricity. In another ERDA study, we focus



solar rays on a field of liquid-metal filled pipes to generate heat. We're working hard on this, but as one engineering wag observes, "In this job, work stops at sunset."

We would not quarrel if you think of McDonnell Douglas as an aerospace company. But, far be it from us to turn away from invention simply because it does not fly. To discuss the technologies mentioned, jot your interest on your letterhead and send it to us. We'll be in touch. Write: McDonnell Douglas, Box 14526, St. Louis, MO 63178.



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EQUAL OPPORTUNITY IN PROFESSIONAL CAREERS. SEND RESUME: BOX 14526, ST. LOUIS, MO. 63178

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

JUNE, 1927: "For several years it has been possible to transmit ordinary photographs by wire and radio, but the problem of sending motion pictures or images of moving objects has been far more intricate. However, the solution has been found, and the results of intensive research and development work have now been shown by the Bell Telephone Laboratories. In the first demonstration two-way telephonic communication was maintained between New York and Washington, D.C., and the images of the various persons in Washington were sent by the new process to the New York terminal of the wires. Secretary Hoover, in Washington, opened the demonstration, and his voice synchronized perfectly with the illuminated image of himself that was cast on a screen in New York. Three telephone lines were used, one for transmitting the voice, one for transmitting the television current and the third for the synchronization of the motors that drove the spinning disks that created the image."

"Dr. E. E. Slosson has worked out for each country what he calls the 'national index of scientific research.' He has taken the list of Nobel prize awards and found out that out of the 72 physics, chemistry, physiology and medicine prizes awarded since 1900 Germany won 21, Great Britain 11, France 10, the Netherlands six, the United States and Sweden four each, Denmark and Switzerland three each, Austria, Italy, Canada and Russia two each and Belgium and Spain one each. This looks as if the Germans won, while we got nowhere. But the Germans did not win, although we got little better than nowhere. It is the Dutch, the Swiss and the Danes who go to the head of the class when you figure it out on the basis of percentage of population. We are not quite at the foot of the class, but nevertheless there is not much satisfaction in our position: Russia stands at the foot and we are next."

"A new wrinkle in radio broadcasting is Great Britain's Advisory Committee on Spoken English, which was formed under the chairmanship of Robert Bridges, the poet laureate. Other members of the Committee are George Bernard Shaw, Sir Johnston Forbes-Robertson, Professor Daniel Jones of the University of London and Logan Pearsall Smith, representing the Society for Pure English. The Committee was formed not to dictate or lay down principles of pronunciation for the country but to introduce uniformity into the forms of pronunciation used by radio-station announcers."

"The Huff, Daland Company's *Cyclops,* the largest single-engine bomber in the world, is now undergoing an exhaustive series of tests by the Army Air Corps at McCook Field in Dayton, Ohio. With full bomb and machine-gun equipment and a crew of eight, the bomber will have a range of 1,000 miles. With gasoline substituted for the bombs and other ordnance, it will be capable of a flight of 24 hours' duration, which could carry it easily from New York to Paris. Perhaps the *Cyclops* will be one of the many airplanes that are to attempt a trans-Atlantic flight this summer."

SCIENTIFIC AMERICAN

JUNE, 1877: "The United States produced last year a cotton crop worth about $250,000,000 and a corn crop worth about $583,000,000. Of a total agricultural product of $4,000,000,000 the corn crop forms the largest item, being more than double the value of the crop that used to be called the King of American Commerce. The King has now laid aside his purple robe and become a respectable citizen who is well received everywhere, but the whole of his estate is far less than that of his plebeian neighbor, Indian Corn, who enters into the business of society in a wonderful variety of forms. His guests sit down to a homely bill of fare, offering hominy, griddle cakes, egg bread, roasting ears, pudding, Johnny cake and popcorn. He shows with pride his well-filled stockyards of corn-fed beeves and porkers, which supply home and foreign markets with the finest meat in the world, from the sweet beefsteak to the fragrant sugar-cured ham fit for the table of a king. He has immense factories employed making starch and syrup, consuming millions of bushels. He runs great distilleries, which send out alcohol enough to float a fleet of war vessels, furnishing material to the arts, revenue to the government, rascality to the whiskey rings and themes to the temperance lecturers."

"The Whitehead torpedo is the secret and the property of the British Admiralty, but the following details have leaked out. These torpedoes resemble in shape a cigar pointed at both ends and are 18 feet long by two feet in diameter. The inside is divided into three different compartments: first, the head, which contains a charge of 350 lb. of gun cotton and the pistol or detonator to explode it; second, the balance chamber, which enables the torpedo to travel at any depth under the water line; and third, the air chamber, which contains the engines and the compressed air to drive them. The Whitehead torpedo can be made to go at the rate of 20 knots for 1,000 yards, and at any depth that is desired from one foot to 30 feet. It is discharged from what is called an impulse tube."

"The electric light, as all are aware, is produced by means of two rods of carbon placed end to end, the extremities being separated by a distance of some hundredths of an inch. Through the carbons a powerful electric current is passed, which causes the production between the ends of an intensely luminous voltaic arc. M. Jablochkoff now discovers that he can dispense with the carbon points and obtain the light by passing the electric current through an insulating material, kaolin clay. He found that, although the current was unable to fuse the kaolin, it did heat it to incandescence. By priming the kaolin plate with a better conductor, he then succeeded in obtaining a brilliant light with a very small consumption of kaolin, so small, indeed, that a kaolin plate barely half an inch in length is sufficient for a small light burning 10 hours."

"Professor A. Graham Bell has recently completed a series of three lectures, in which he introduced his speaking telephone to New York audiences. There can be no question but that the instrument is a most wonderful invention. Without the aid of any battery, using only the current induced in the circuit by its permanent magnet, the telephone on the occasion of the last lecture transmitted musical sounds and speech from Yonkers to New York, a distance of 26 miles. With the battery attached, melodies and chords played on a small organ at Yonkers were distinguishable throughout the large hall where the lecture took place."

"A new mania is at hand, to wit the celery cure. 'Celery is the greatest food in the world for the nerves,' says one of our contemporaries, and the information is traveling the length and breadth of the land. It is fashionable nowadays to call every ailment that flesh is heir to a nervous disease, and where our ancestors would have resorted to such homely remedies as a hot drink and simple cathartics, the present practice demands chloral, bromides, quinine, strychnine and phosphates. Of course, celery is pleasanter to take than most drugs, and now that it is brought forward as a new nervine plenty of people will use it. As it can do no harm, and indeed may actually work good by checking the too prevalent consumption of 'nervous specifics,' the mania is rather a benefit than otherwise and should doubtless be encouraged."

THE AUTHORS

BERNARD L. COHEN ("The Disposal of Radioactive Wastes from Fission Reactors") is professor of physics and of chemical engineering and petroleum engineering at the University of Pittsburgh. He is also director of the university's Scaife Nuclear Laboratories. He received his B.S. from the Case Institute of Technology in 1944, his M.S. from the University of Pittsburgh in 1948 and his D.Sc. from the Carnegie Institute of Technology in 1950. From 1950 through 1958 he was group leader of cyclotron research at the Oak Ridge National Laboratory. He has been with the University of Pittsburgh since 1958. Cohen is the author of two books on nuclear physics and one on nuclear science and society. He writes: "My principal work over the years has been basic research in nuclear physics using cyclotrons and Van de Graaff accelerators. In 1969 I began investigating how nuclear techniques might be applied to biomedical and environmental studies. In 1971 I developed a program to study the environmental impact of nuclear engineering, and I now spend nearly half of my research effort in that area."

EDNOR M. ROWE and JOHN H. WEAVER ("The Uses of Synchrotron Radiation") are respectively director and assistant scientist at the Synchrotron Radiation Center of the University of Wisconsin at Madison. Rowe received his B.S. in physics from Purdue University in 1954. At that time he became involved with the newly formed Midwestern University Research Association (MURA), which had been organized to study advanced concepts of accelerator design. He remained with MURA for 13 years, supervising the construction of accelerators and investigating related technologies. In 1967 MURA was disbanded, and the laboratory and staff became part of the University of Wisconsin. Rowe has been director of the Synchrotron Radiation Center at Wisconsin since 1970 and has been active in the development of synchrotron-radiation research both nationally and internationally. His principal interest is in the application of particle accelerators and their technologies to areas outside nuclear physics and high-energy physics. Weaver has been a member of the scientific staff at the Synchrotron Radiation Center since 1974. He received his bachelor's and master's degrees in physics at the University of Missouri at Kansas City. After completing his Ph.D. in solid-state physics at Iowa State University in 1973, he spent a year as a postdoctoral fellow at the University of Missouri at Rolla. He joined the Synchrotron Radiation center in 1974. Weaver's own research is concerned with the electronic structure of matter, particularly transition, rare-earth and actinide metals.

HOLGER W. JANNASCH and CARL O. WIRSEN ("Microbial Life in the Deep Sea") are members of the biology department of the Woods Hole Oceanographic Institution. Jannasch, a native of Germany, studied microbiology at the universities of Munich and Göttingen, receiving his Ph.D. from Göttingen in 1955. As a research assistant with the Max Planck Society, he worked at the Scripps Institution of Oceanography and at the University of Wisconsin at Madison. He joined the Woods Hole Oceanographic Institution as a senior scientist in 1963. Since 1971 he has also been the director of a summer course in microbial ecology at the Marine Biological Laboratory in Woods Hole. In addition to deep-sea microbiology Jannasch is interested in the dynamics of the growth, survival and population of marine bacteria and in bacteria that metabolize sulfur. Wirsen received his M.A. from Boston University in 1966 and then worked as a research associate at Harvard University. He has been at the Woods Hole Oceanographic Institution since 1968.

ROBERT L. DICKMAN ("Bok Globules") is a research associate in the physics department of the Rensselaer Polytechnic Institute, working at the millimeter-wave radio facility of the Aerospace Corporation in Los Angeles. He received his bachelor's, master's and doctor's degrees from Columbia University. "My basic field of research is observational studies of interstellar molecules," he writes. "I have been investigating questions relating to the gravitational stability of Bok globules, the abundances of isotopes of carbon monoxide in interstellar dark clouds and the mechanisms by which molecules in such clouds emit their radiation."

DAVID S. OLTON ("Spatial Memory") is associate professor in the department of psychology at Johns Hopkins University. He studied under Robert L. Isaacson at the University of Michigan, where he developed his interest in spatial memory. The experiments with radial-arm mazes described in his article were an unexpected development of an experiment he began with Robert Samuelson, an undergraduate at Johns Hopkins. "I've always had an interest in spatial learning, perhaps because I have so much difficulty with spatial relations myself," Olton writes. "When I saw how well animals performed on the radial-arm-maze test, I knew we could significantly advance the understanding of spatial abilities in animals and of the physiological basis of those abilities."

WILLIAM A. SILVERMAN ("The Lesson of Retrolental Fibroplasia") is a medical consultant for the California Department of Rehabilitation. After being graduated from the University of California Medical School he received his intern and residency training at the University of California Hospital in San Francisco. In 1944 he went to Babies Hospital of the Columbia-Presbyterian Medical Center; he remained there for nearly 25 years and also became professor of pediatrics at the Columbia University College of Physicians and Surgeons. Silverman became deeply involved with the medical problems of premature infants, particularly with the epidemic of blindness that erupted when the first premature-baby center was opened at Babies Hospital in 1950. After the epidemic subsided Silverman and his colleague John Fertig, professor of biostatistics at Columbia's School of Public Health, employed strategies of randomized clinical trials to investigate the effects of the physical environment on the well-being of premature infants.

NATHAN SHARON ("Lectins") is head of the department of biophysics at the Weizmann Institute of Science in Israel. He has been at the Weizmann Institute since 1954. From 1956 through 1958 and again during the academic year 1962–63 he was a research fellow at the Harvard Medical School; from 1970 through 1971 he was visiting professor in the department of biochemistry at the University of California at Berkeley. Currently he is interested primarily in the structure and biological function of sugars on cell membranes, and he is employing lectins as one of his main research tools.

MARGARET M. BYARD ("Poetic Responses to the Copernican Revolution") is a literary historian. After receiving her early education in Scotland and England, she came to the U.S. and was graduated from Smith College in 1933. In 1962 she received her Ph.D. in English from Columbia University; there she studied under Marjorie Hope Nicolson, a literary historian and a pioneer in demonstrating the interaction of science and literature in history. After working for *The New York Times* and *Time*, Byard taught 17th-century literature at Hunter College, at Douglass College of Rutgers University and at the School of General Studies of Columbia University. She retired from Columbia in 1972. Byard has concentrated on studying the cross-fertilization of ideas between science and poetry and between music and poetry. She is now working on an anthology of space poetry, tentatively titled *A Sky Watcher's Companion*.

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The Disposal of Radioactive Wastes from Fission Reactors

A substantial body of evidence indicates that the high-level radioactive wastes generated by U.S. nuclear power plants can be stored satisfactorily in deep geological formations

by Bernard L. Cohen

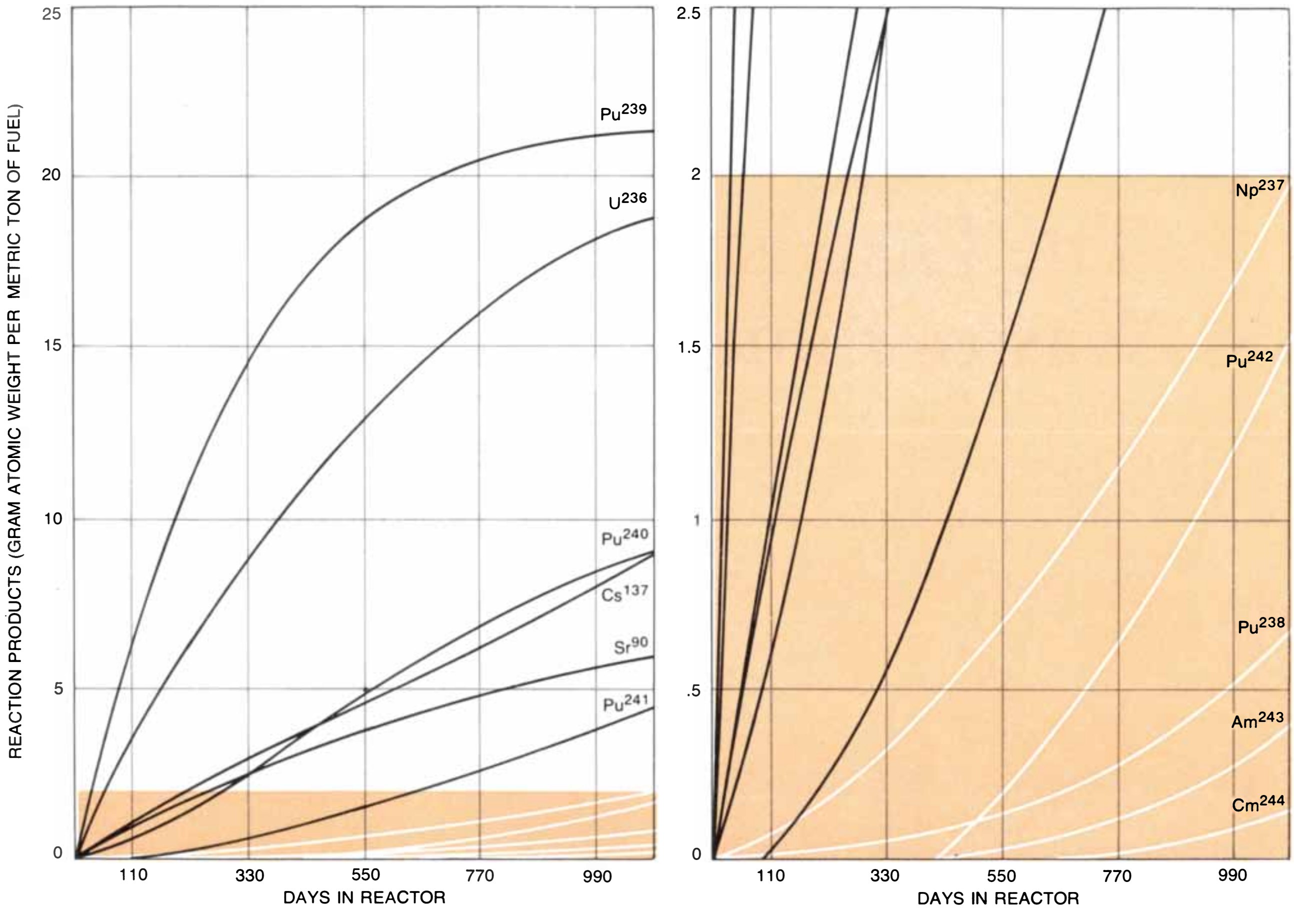
The task of disposing of the radioactive wastes produced by nuclear power plants is often cited as one of the principal drawbacks to the continued expansion of this country's capacity to generate electricity by means of the nuclear-fission process. Actually the task is not nearly as difficult or as uncertain as many people seem to think it is. Since 1957, when a committee of the National Academy of Sciences first proposed the burial of such wastes in deep, geologically stable rock formations, a substantial body of evidence has accumulated pointing to the technical feasibility, economic practicality and comparative safety of this approach. In recent years a number of alternative schemes—some of them involving undersea burial—have also been put forward, but deep underground burial remains the best understood and most widely favored solution to the problem of nuclear-waste disposal.

In what follows I shall describe the nature of the wastes produced by nuclear power reactors, evaluate their potential impact on public health and the environment and outline current plans to dispose of them in secure underground repositories.

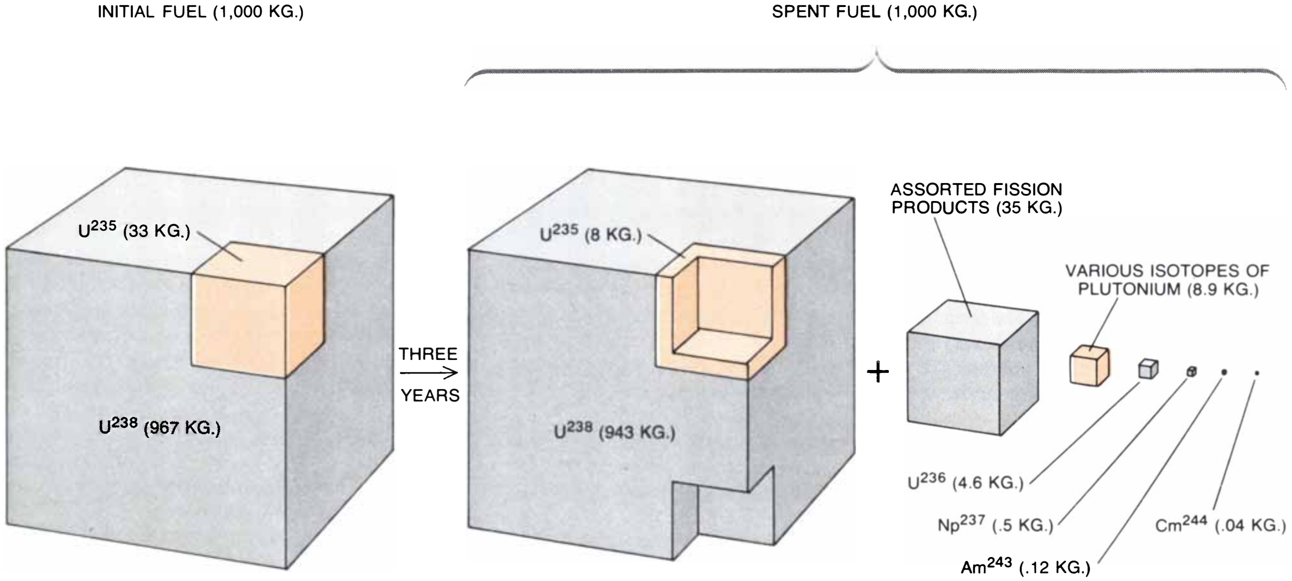
What are the special characteristics of nuclear-plant wastes, and how do they differ from the wastes produced by the combustion of other fuels to generate electricity? For the sake of comparison it might be helpful to consider first the wastes resulting from the operation of a large (1,000-megawatt) coal-burning power plant. Here the principal waste is carbon dioxide, which is emitted from the plant's exhaust stacks at a rate of about 600 pounds per second. Carbon dioxide is not in itself a dangerous gas, but there is growing concern that the vast amounts of it being released into the atmosphere by the combustion of fossil fuels may have deleterious long-term effects on the world's climate. The most harmful pollutant released by a coal-burning power plant is sulfur dioxide, which is typically emitted at a rate of about 10 pounds per second. According to a recent study conducted under the auspices of the National Academy of Sciences, sulfur dioxide in the stack effluents of a single coal-fired plant causes annually about 25 fatalities, 60,000 cases of respiratory disease and $12 million in property damage. Among the other poisonous gases discharged by coal-burning power plants are nitrogen oxides, the principal pollutants in automobile exhausts (a large coal-fired plant releases as much of these as 200,000 automobiles do), and benzpyrene, the main cancer-causing agent in cigarettes. Solid wastes are also produced, partly in the form of tiny particles. In the U.S. today such "fine particulate" material is considered second in importance only to sulfur dioxide as an air-pollution hazard; approximately a sixth of all man-made fine-particulate pollution comes from coal-burning power plants. Finally there is the residue of ashes, which for a 1,000-megawatt coal-fired plant accumulate at a rate of about 30 pounds per second.

The wastes from a nuclear power plant of equivalent size differ from the by-products of coal combustion in two important ways. First, their total quantity is millions of times smaller: when the wastes are prepared for disposal, the total volume produced annually by a 1,000-megawatt nuclear reactor is about two cubic meters, an amount that would fit comfortably under a dining-room table. The comparatively small quantities of radioactive materials involved here make it practical to use highly sophisticated waste-management procedures, whose cost must be viewed in relation to the price of the electricity generated. For a 1,000-megawatt plant that price is roughly $200 million per year.

The second distinguishing characteristic of nuclear wastes is that their potential as a health hazard arises not from their chemical properties but from the radiation they emit. There appears to be a widespread misapprehension that this factor introduces a considerable degree of uncertainty into the evaluation of the potential health hazards associated with nuclear wastes, but the truth is quite the opposite. The effects of radiation on the human body are far better understood than the effects of chemicals such as air pollutants, food additives and pesticides. Radiation is easy to measure accurately with inexpensive but highly sensitive instruments; indeed, that is why radioactive isotopes are used so widely in biomedical research. Moreover, a large body of information has been compiled over the years from human exposure to intense radiation, including the atomic-bomb attacks on Japan, medical treatment with different forms of radiation and the inhalation of radon gas by miners. The available data have been analyzed intensively by national and international groups, including the National Academy of Sciences Committee on the Biological Effects of



BUILDUP OF REACTION PRODUCTS per metric ton (1,000 kilograms) of uranium fuel in the active core of a typical U.S. power reactor of the light-water type is plotted here on two different vertical scales as a function of time over the three-year period the fuel customarily resides in the core. The hundreds of products resulting from the fission of uranium-235 nuclei in the fuel are represented by two characteristic fission fragments, strontium 90 and cesium 137, which together constitute about 5 percent of the total. All the other isotopes shown result from nuclear reactions in which uranium nuclei in the initial fuel are transmuted by neutron-capture reactions, followed in some cases by radioactive decay. Leveling off of the curve for fissionable plutonium 239 means that near the end of the effective life of the fuel this isotope is being consumed by fission reactions and neutron-capture reactions almost as fast as it is being created.



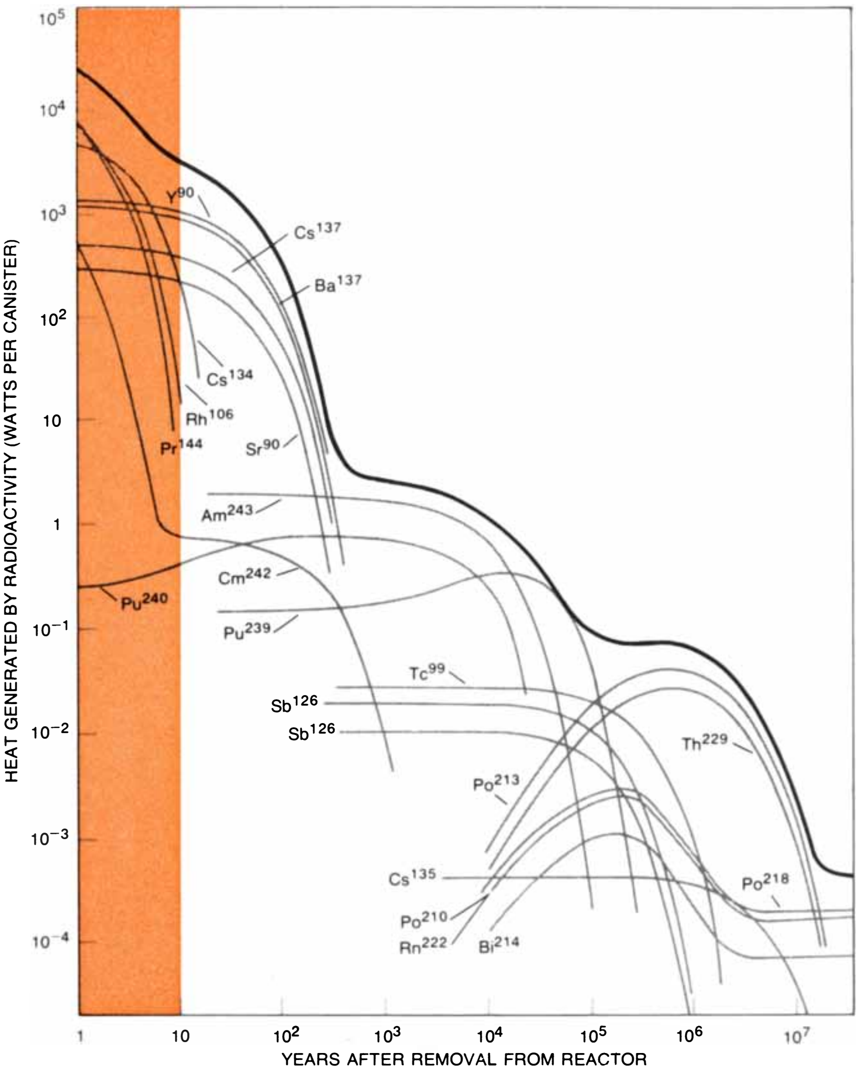
BLOCK DIAGRAM provides another graphic view of the transformation that takes place in the composition of the nuclear fuel in a light-water reactor over a three-year period. For every 1,000 kilograms of uranium in the initial fuel load (*left*) 24 kilograms of uranium 238 and 25 kilograms of uranium 235 are consumed (*center*), reducing the "enrichment" of uranium 235 from 3.3 percent to .8 percent. Uranium that is consumed is converted into 35 kilograms of assorted fission products, 8.9 kilograms of various isotopes of plutonium, 4.6 kilograms of uranium 236, .5 kilogram of neptunium 237, .12 kilogram of americium 243 and .04 kilogram of curium 244 (*right*).

Ionizing Radiation and the United Nations Scientific Committee on the Effects of Atomic Radiation. The result is a fairly reliable set of estimates of the maximum effects of various levels of radiation on the human body.

What are the radioactive substances in the waste products of a nuclear reactor, and how are they formed? In a light-water reactor (the type of nuclear plant now in general service for generating electricity in this country) the fuel consists initially of a mixture of two isotopes of uranium: the rare, readily fissionable isotope uranium 235 ("enriched" to 3.3 percent) and the abundant, ordinarily nonfissionable isotope uranium 238 (96.7 percent). The fuel mixture is fabricated in the form of ceramic pellets of uranium dioxide (UO_2), which are sealed inside tubes of stainless steel or a zirconium alloy. In the course of the reactor's operation neutrons produced initially by the fission of some of the uranium-235 nuclei strike other uranium nuclei, either splitting them in two (and thereby continuing the chain reaction) or being absorbed (and thereby increasing the atomic weight of the struck nucleus by one unit). These two types of reaction result in a variety of nuclear products, which can be plotted as a function of the time the fuel is in the reactor, usually about three years [*see top illustration on opposite page*].

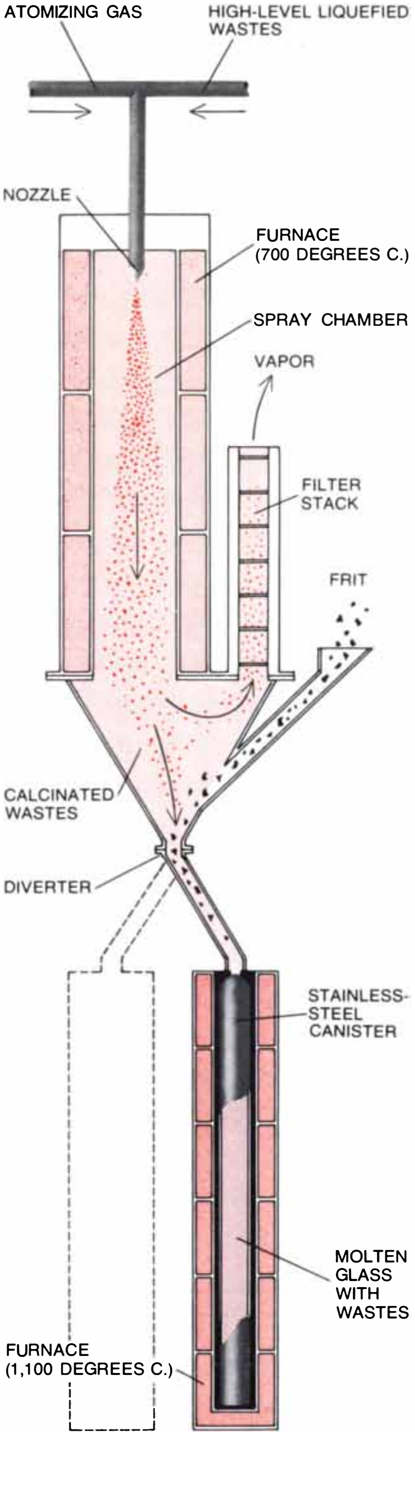
The most important reaction in a light-water reactor is the fission of uranium 235, which creates hundreds of different products, of which strontium 90 and cesium 137, two characteristic fission fragments, constitute about 5 percent of the total. Another important reaction is the capture of neutrons by uranium-238 nuclei, which gives rise to plutonium 239. (Actually the neutron-capture reaction first yields uranium 239, which then decays radioactively in two steps to plutonium 239.) The plutonium 239 does not continue to build up linearly with time, because it may also participate in nuclear reactions. For example, a nucleus of plutonium 239 may fission when it is struck by a neutron, or it may absorb the neutron to become a nucleus of plutonium 240. The leveling off of the plutonium-239 curve means that near the end of the effective life of the fuel load this isotope is being destroyed by such processes at nearly the same rate as the rate at which it is being created.

Plutonium 240 can also capture a neutron and become plutonium 241, which can in turn either fission or capture another neutron and become plutonium 242. Plutonium 242 can be converted by the capture of still another neutron into americium 243 (after an intermediate radioactive decay from plutonium 243), and there is even an appreciable amount of curium 244 created by an additional neutron capture followed by a radioactive decay. By the same token successive neutron captures beginning with uranium 235 can respectively give rise to uranium 236, neptunium 237 and plutonium 238.



HEAT GENERATED by the various radioactive isotopes in the spent fuel from a nuclear power plant must be allowed to dissipate safely, which means that in any long-term storage plan the canisters containing the high-level wastes must be spread out over a fairly large area. The problem can be substantially alleviated by resorting to an interim-storage period of about 10 years (*colored panel at left*), after which the heat generated by each canister will have fallen off to about 3.4 kilowatts. The gray curves trace the contributions of the more important radioactive isotopes to the overall heating effect, which in turn is indicated by the black curve.

For every metric ton (1,000 kilograms) of uranium in the initial fuel load 24 kilograms of uranium 238 and 25 kilograms of uranium 235 are consumed in the three-year period, reducing the enrichment of the uranium 235 from 3.3 percent to .8 percent. In the process 800 million kilowatt-hours of electrical energy can be generated, and the uranium that is consumed is converted into 35 kilograms of assorted fission products, 8.9 kilograms of various isotopes of plutonium, 4.6 kilograms of uranium 236, .5 kilogram of neptunium 237, .12 kilogram of americium 243 and .04 kilogram of curium 244. Since only 25 kilograms of uranium 235 are consumed and a fifth of that amount is converted into uranium 236 and neptunium 237, one can easily calculate that only 60 percent of the energy-releasing fission reactions actually take place in uranium 235. Thirty-one percent occur in plutonium 239, 4 percent occur in plutonium 241 and 5 percent are induced by high-energy neutrons in uranium 238. (These figures are averages over the three years the fuel customarily is in the reactor. Near the end of that period only 30 percent of the fission reactions take place in uranium 235, with 54 percent occurring in plutonium 239, 10 percent in plutonium 241 and 5 percent in uranium 238. In view of the current public controversy over the projected future recycling of plutonium in nuclear reactors, it is inter-



CURRENT PLAN for handling high-level radioactive wastes calls for their incorporation into glass cylinders about 300 centimeters long and 30 centimeters in diameter. In the single-step solidification process depicted here the liquid high-level waste is first converted into a fine powder inside a calcining chamber (*top*), then mixed with glassmaking frit (*middle*) and finally melted into a block of glass within the thick stainless-steel canister in which it will eventually be stored (*bottom*). When canister is full, flow is switched by a diverter valve into a new canister (*broken outline*); hence the process is continuous.

esting to note that plutonium is already in intensive use as a nuclear fuel.)

After the spent fuel is removed from the reactor it is stored for several months in order to allow the isotopes with a short radioactive half-life to decay. (This temporary storage is particularly important with respect to an isotope such as iodine 131, one of the most dangerous fission products, which has a half-life of only eight days.) Thereafter one of the options would be to send the spent fuel to a chemical-reprocessing plant, where the fuel pins would be cut into short lengths, dissolved in acid and put through a series of chemical-separation processes to remove the uranium and plutonium, which would then be available to make new fuel. Everything else (except for certain gases, which would be discharged separately, and the pieces of the metal fuel pins that do not dissolve in the acid) is referred to as "high level" waste. In addition to all the fission products, which are responsible for the bulk of the radioactivity, the high-level wastes would in this case include the isotopes of neptunium, americium and curium, along with the small amounts of uranium and plutonium that would not be removed in reprocessing, owing to inefficiencies in the chemical separations.

The simplest and most obvious way to dispose of the remaining high-level wastes (once an economically sufficient quantity of them began to accumulate) would be to bury them permanently deep underground. On the face of it such an approach appears to be reasonably safe, since all rocks contain traces of naturally radioactive substances such as uranium, thorium, potassium and rubidium, and the total amount of this natural radioactivity in the ground under the U.S. down to the proposed nuclear-waste burial depth of 600 meters is enormously greater than the radioactivity in the wastes that would be produced if the country were to generate all its electric power by means of nuclear fission. Of course, the radioactivity of the nuclear wastes is more concentrated, but in principle that does not make any difference; the biological effects of radiation are generally assumed to have a linear relation to dosage, so that distributing a given total dosage among more people would not change the number of adverse health effects. (If this "linearity hypothesis" were to be abandoned, current estimates of the potential health hazards from nuclear wastes and all other aspects of the nuclear power industry would have to be drastically reduced.)

The detailed procedures for handling the high-level wastes are not yet definite, but present indications are that the wastes will be incorporated into a borosilicate glass (similar to Pyrex), which will be fabricated in the form of cylinders about 300 centimeters long and 30 centimeters in diameter. Each glass cylinder will in turn be sealed inside a thick stainless-steel casing. These waste canisters will then be shipped to a Federally operated repository for burial. One year's wastes from a single 1,000-megawatt nuclear power plant will go into 10 such canisters, and the canisters will be buried about 10 meters apart; hence each canister will occupy an area of 100 square meters, and all 10 canisters will take up 1,000 square meters. It has been estimated that an all-nuclear U.S. electric-power system would require roughly 400 1,000-megawatt plants, capable of generating 400,000 megawatts at full capacity, compared with the present average electric-power usage of about 230,000 megawatts. Accordingly the total high-level wastes generated annually by an all-nuclear U.S. electric-power system would occupy an area of less than half a square kilometer.

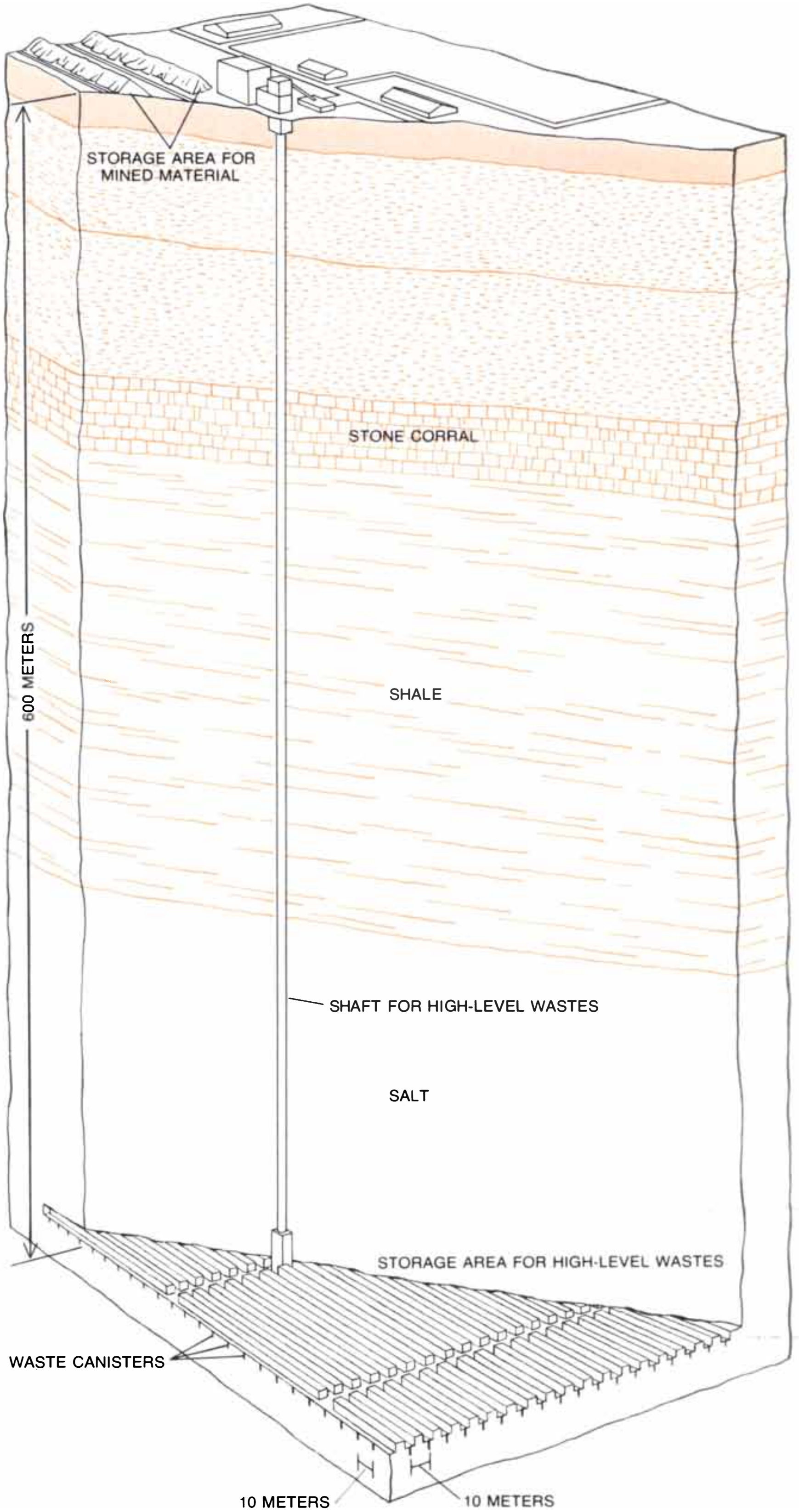
The main reason for spreading the canisters over such a large area is to dissipate the heat generated by their radioactivity. The problem of dealing with this heat can be substantially alleviated by waiting for 10 years after the reprocessing operation, at which time the heat generated by each canister will have fallen off to about 3.4 kilowatts. The advantage of delayed burial is seen more clearly when the heating effect is translated into the estimated rise in temperature that would result at the surface of a canister buried alone in rock of average thermal conductivity [*see top illustration on page 26*]. It is evident that burial after a wait of a year would lead to a temperature rise of 1,900 degrees Celsius, whereas waiting for 10 years would reduce the rise to 250 degrees C. The difference is critical, since glass devitrifies (crystallizes and becomes brittle) at temperatures higher than 700 degrees. In rock of average thermal conductivity the maximum average temperature of the rock just above and below the burial depth would be reached 40 years after burial, when the average temperature at the burial depth would be increased by 140 degrees [*see bottom illustration on page 26*]. If the canister were to be buried in salt, which has a much greater thermal conductivity, the rise in temperature at the burial depth after 40 years would be less: 85 degrees.

In salt an additional effect must be taken into account, since the heat will cause the migration of water toward the waste canister. Typical salt formations contain about .5 percent water trapped in tiny pockets. The solubility of salt in water increases with temperature, so that if the temperature on one side of the pocket is raised, more salt will go into solution on that side. This raises the salt content of the water above the saturation point for the temperature on the opposite side of the pocket, however, causing the salt to precipitate out of solution on that side. The net effect is a migration of the water pocket in the direction of the higher temperature, which is of course the direction of the buried waste canister. The rate of the migration depends on how rapidly the temperature increases with distance, and on how rapidly the temperature gradient, as I have explained, falls off with time.

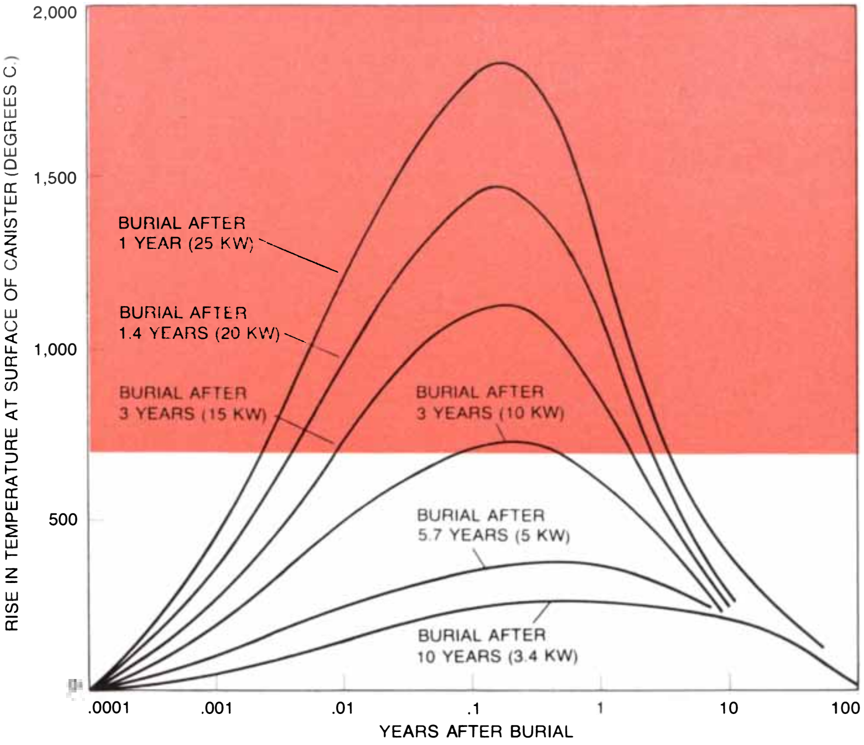
This process is expected to lead to the collection of water around each canister at an initial rate of two or three liters per year; within 25 years a total of 25 liters will have collected, with very little further collection expected thereafter. Since the temperature at the surface of the canister would be higher than the boiling point of water, the water arriving at the canister would be converted into steam and would be drawn off by the ventilation system (assuming that the repository is not sealed). Small amounts of water would continue to migrate toward the canisters after 25 years, carrying corrosive substances such as hydrochloric acid arising from chemical reactions induced in the salt by the radiation from the canister. It is therefore usually assumed that the stainless-steel casings will corrode away, leaving the waste-containing glass cylinders in contact with the salt.

How can one evaluate the health hazards presented by such radioactive waste materials? The most direct hazard is from the gamma radiation emitted by the decaying nuclei. Gamma rays behave much like X rays except that they are even more penetrating. The effect of gamma rays (or any other form of ionizing radiation) on the human body is measured in the units called rem, each of which is equal to the amount of radiation that is required to produce the same biological effect as one roentgen of X radiation. ("Rem" stands for "roentgen equivalent man.") In analyzing the impact of radioactive wastes on public health the only significant radiation effects that need to be considered are those that cause cancer and those that induce genetic defects in progeny. According to the best available estimates, for whole-body radiation such as would be delivered by a source of gamma rays outside the body the risk of incurring a radiation-induced fatal cancer is approximately 1.8 chances in 10,000 per rem of radiation exposure. The estimated risk for total eventual genetic defects in progeny is about 1.5 chances in 10,000 per rem of radiation delivered to the gonads (with the effects spread out over about five generations). In the discussion that follows I shall be referring only to cancers, but it should be kept in mind that there are in addition a comparable (but generally smaller) number of genetic defects caused by exposure to gamma radiation.

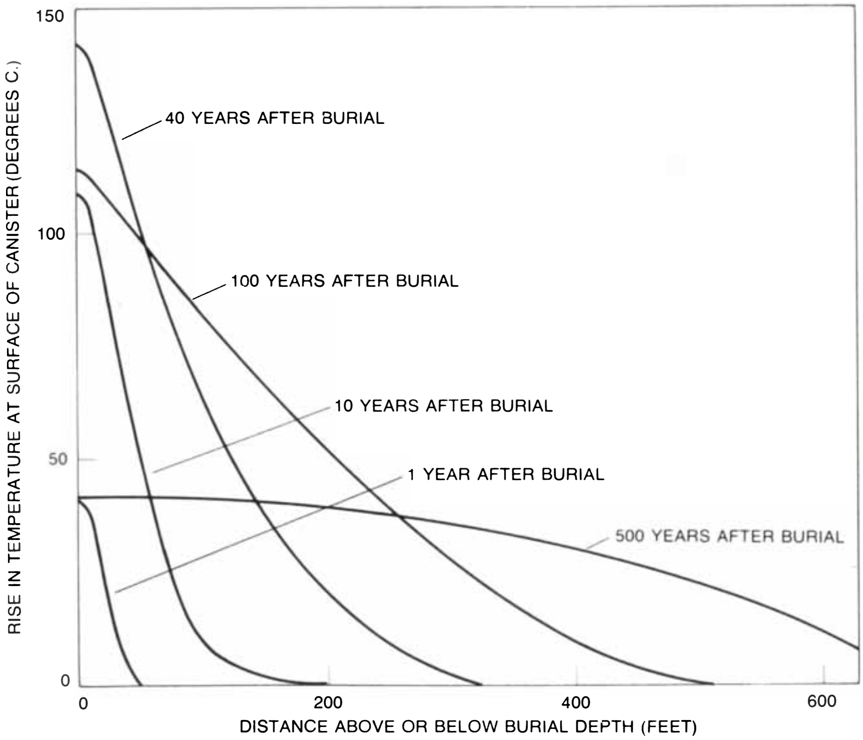
The biological damage done by a gamma ray is in most situations roughly proportional to the ray's energy, so that



DEEP UNDERGROUND BURIAL is at present the method favored by most nuclear power experts in the U.S. for the long-term storage of high-level radioactive wastes. In this idealized diagram of a proposed Federally operated repository in southeastern New Mexico the waste canisters are shown emplaced at a depth of 600 meters in a geologically stable salt formation. In order to dissipate the heat from the canisters they would be buried about 10 meters apart; thus each canister would occupy an area of about 100 square meters. On this basis the total high-level wastes generated annually by an all-nuclear U.S. electric-power system (assuming roughly 400 1,000-megawatt plants) would occupy an area of less than half a square kilometer.



ADVANTAGE OF DELAYED BURIAL is evident in this graph, in which the heating effect of a single waste canister is translated into the estimated rise in temperature that would result at the surface of the canister if it were buried alone in rock of average thermal conductivity. The numbers labeling each curve indicate the heat generated by the canister (in kilowatts) after a given interim-storage period (in years). Thus burial after one year (*top curve*) would cause a temperature rise of 1,900 degrees Celsius, whereas waiting for 10 years (*bottom curve*) would reduce the increment to 250 degrees C. Colored area at top symbolizes critical fact that glass devitrifies (crystallizes and becomes brittle) at temperatures higher than 700 degrees C.



MAXIMUM AVERAGE TEMPERATURE of the rock just above and below the burial depth of the waste canister would be reached 40 years after burial, when the average temperature at the burial depth would be increased by about 140 degrees C. If the waste canister were to be buried in salt, the corresponding temperature increments would be considerably reduced.

one first plots the gamma-ray energy emitted per second (in watts) by the wastes resulting from one full year of a U.S. energy budget based on all-nuclear generation of electric power [*see bottom illustration on opposite page*]. From such a graph one can see that for the period between eight and 400 years after reprocessing the dominant contribution to the total gamma-ray emission is made by cesium 137 and its immediate decay product barium 137. During this four-century period the total gamma-ray hazard falls by more than four orders of magnitude.

One way to grasp the potential hazard presented by this amount of gamma radiation is to consider what would happen if the source of radiation were to be distributed over the entire land surface of the U.S. The number of fatal cancers per year induced in that case could be as high as many millions. Clearly the material that gives rise to the radiation must be confined and handled with great care. On the other hand, gamma rays are attenuated by about a factor of 10 per foot in passing through rock or soil, so that there would be no danger of this type from wastes that remain buried deep underground.

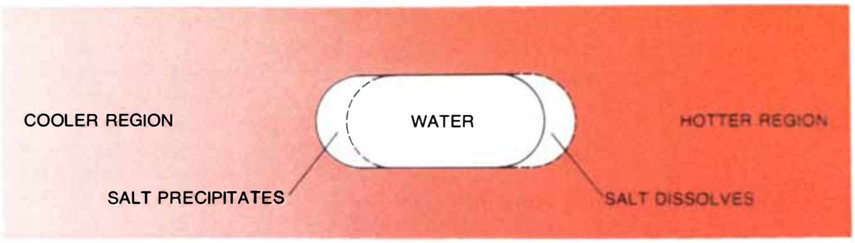
A measure of the care that must be taken in handling the waste canisters is indicated by the fact that a dose of 500 rem (which has a 50 percent chance of being fatal) would be received in 10 minutes by a human being standing 10 meters away from an unshielded new waste canister. There is no great technical difficulty, however, in providing shielding adequate for safe and effective remote handling of the waste canisters.

If any of the radioactive wastes were to enter the human body, their biological effects would be enhanced, since the radiation they would emit would strike human tissue in all directions and since the exposure would continue for some time. Accordingly one must consider the two major possible entry routes: ingestion and inhalation. The ingestion hazard can be evaluated in terms of the number of cancer-causing doses in the wastes produced by one year of all-nuclear electric power in the U.S. [*see illustration on page 28*]. In this graph the value of 10^6 at 10^4 years, for example, means that if all the wastes, after aging for 10,000 years, were to be converted into digestible form and fed to people, one could expect a million fatal cancers to ensue. This "worst case" scenario assumes, of course, that many millions of people are involved, but in view of the linear relation between dose and effect generally assumed for calculating such radiation risks it does not matter how many millions there are. The derivation of such a graph is rather complex, involving for each radioactive species the probability of transfer across the intestinal wall into the bloodstream; the probability of transfer from the blood into each body organ; the time the radioactive substance spends in each organ; the energy of the radiation emitted by the substance and the fraction of the energy absorbed by the organ; the mass of the organ; the relative biological effects of the different kinds of radiation emitted, and finally the cancer risk per unit of radiation absorbed (in rem).

Feeding all this radioactive material to people is hardly a realistic scenario, however, so that one might consider instead the consequences if the wastes were to be dumped in soluble form at random into rivers throughout the U.S. For this scenario, which comes close to assuming the most careless credible handling of the disposal problem, the graph shows that a million fatalities could result. It is unlikely anyone would suggest such dumping, but in any event it is clearly not an acceptable method of disposal.

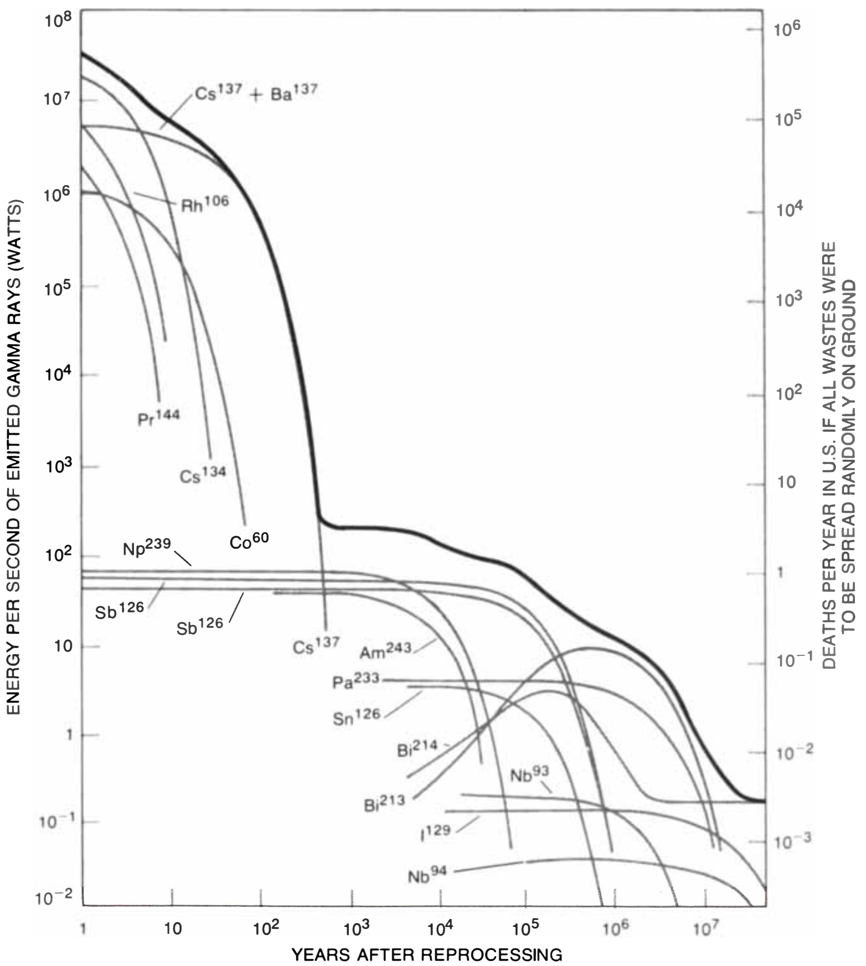
In evaluating the inhalation hazard by far the most important effect that must be taken into account is the induction of lung cancers [*see illustration on page 29*]. Here again the graph shows the consequences of a situation approximating the most careless credible handling of the wastes: spreading them as a fine powder randomly over the ground throughout the U.S. and allowing them to be blown about by the wind.

Much attention is given in public statements to the potential hazards represented by the scales in such graphs that show the number of cancers expected if all the radioactive materials involved were to be ingested or inhaled by people. One often hears, for example, that there is enough radioactivity in nuclear wastes to kill billions of people. To put such statements in perspective it is helpful to compare the known hazards of nuclear wastes with those of other poisonous substances used in large quantities in the U.S. [*see illustration on page 30*]. Such a comparison shows that there is nothing uniquely dangerous about nuclear wastes. Nevertheless, it is often emphasized that radioactive wastes remain hazardous for a long time. Nonradioactive barium and arsenic, on the other hand, remain poisonous forever. It might also be argued that the other hazardous substances are already in existence, whereas nuclear wastes are a newly created hazard. Roughly half of the U.S. supply of barium and arsenic, however, is currently imported, and hence these hazards are also being introduced "artificially" into our national environment. One other important difference often goes unnoted, and that is that the chemical poisons are not carefully buried deep underground as is the plan for the nuclear wastes; indeed, much of the arsenic is used as a herbicide and hence is routinely scattered around on the ground in regions where food is grown.



IN SALT the heat from the waste canister would cause the migration of tiny pockets of water in the direction of the higher temperature, since the salt would tend to go into solution on the hotter side of the pocket (*right*) and to precipitate out of solution on the cooler side (*left*).

Actually such quantitative representations of potential hazards are virtually meaningless unless one also takes into account the possible pathways the hazardous agents can take to reach man. Therefore I shall now turn to that subject. It is generally agreed the most important health hazard presented by nuclear wastes arises from the possibility that ground water will come in contact with the buried wastes, leach them into solution, carry them through the overlying rock and soil and ultimately into food and water supplies. Human exposure would then be through ingestion. From the analysis of the ingestion route outlined above one can deduce that the hazard from ingested radioactive mate-



MOST DIRECT HEALTH HAZARD presented by radioactive wastes arises from the gamma radiation emitted by the decaying nuclei. The biological damage done by a gamma ray is in most situations roughly proportional to its energy; hence in this graph the gamma-ray energies emitted per second by various radioactive isotopes in the wastes resulting from one full year of an all-nuclear U.S. electric-power system (again assuming 400 1,000-megawatt plants) are plotted according to the scale at left. The black curve shows that between eight and 400 years after reprocessing the total gamma-ray hazard falls by more than four orders of magnitude. Scale at right indicates the total number of fatal cancers expected per year if the source of this amount of gamma radiation were to be spread at random over entire land surface of the U.S.

rial is high at first but much less after a few hundred years. In fact, one can calculate that after 600 years a person would have to ingest approximately half a pound of the buried waste to incur a 50 percent chance of suffering a lethal cancer. It is reasonable to conclude that it is very important the wastes be isolated from human contact for the initial few hundred years. I shall first take up that problem but shall return to the longer-term one.

When people first learn that nuclear wastes must be isolated for hundreds of years, their immediate response is often to say this is virtually impossible: man's social institutions and political systems and the structures he builds rarely last that long. This response, however, is based on experience in the environment encountered on the surface of the earth. What one is actually dealing with are rock formations 600 meters below the surface. In this quite different environment the characteristic time intervals required for any substantial change are on the order of millions of years.

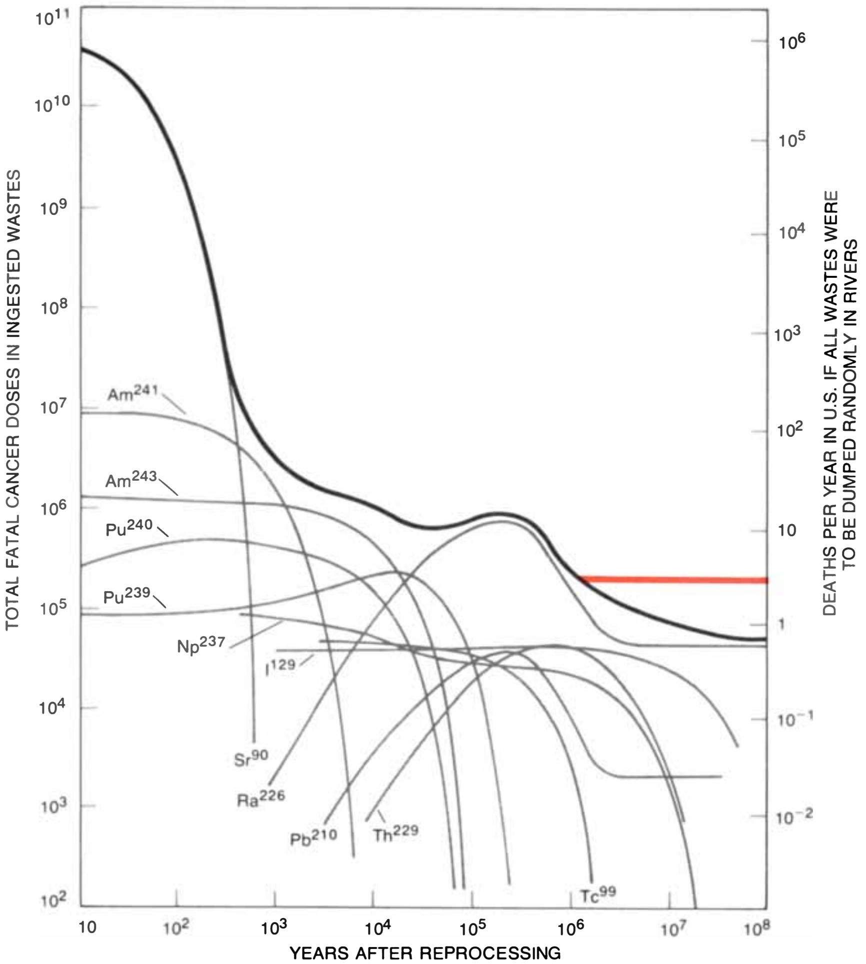
In addition to the general security of the deep underground environment a great deal of extra protection is provided for the critical first few hundred years by the various time delays intrinsic to any conceivable release process. The most important of these additional safeguards has to do with the selection of a storage site, which is determined by geological study to be not only free of circulating ground water now but also likely to remain free of it for a very long time to come. In geological terms a few hundred years is a short time, so that predictions of this kind can be highly reliable. Since the patterns in which groundwater flows can be changed by earthquakes, only tectonically stable areas would be chosen. Salt formations offer additional security in this regard, because when salt is subjected to pressure, it flows plastically. Thus it is capable of sealing cracks that develop from tectonic activity. This property of salt also removes the scars of the burial operations, leaving the canisters sealed deep inside a gigantic crystalline mass.

Suppose, however, water does somehow manage to get into cracks in the rock formation in which the waste is buried. What happens then? The rock would of course be chosen to be impervious to water, so that there would be a second delay while the rock was being leached away before the waste glass was exposed to water. It would seem that there would not be much delay in salt because it is so soluble in water, but in fact the quantities of water deep underground are not large and the mass of salt is huge. For example, if all the ground water now flowing in the region of the proposed Federal waste-repository site in New Mexico were somehow diverted to flow through the salt, it would take 50,000 years for the salt enclosing one year's deposit of nuclear wastes to be dissolved away.

A third delay arises from the time it would take to leach away the waste glass itself. There is some uncertainty on this point, and the matter is complicated by the fact that leaching rates increase rapidly with temperature, but it seems fairly certain that the low rate at which the glass can be leached away will offer considerable protection for at least a few hundred years. If new leaching-rate studies indicate otherwise, it would not be too difficult or expensive to switch to ceramics or other more resistant materials for incorporating the wastes.

A fourth delay arises from the length of time it ordinarily takes water to reach the surface. Typical flow rates are less than 30 centimeters per day, and typical distances that must be covered are tens or hundreds of kilometers. For anything to travel 100 kilometers at 30 centimeters per day takes about 1,000 years.

The radioactive wastes would not, however, move with the velocity of the ground water even if they went into solution. They would tend to be filtered out by ion-exchange processes. For example, an ion of radioactive strontium in the wastes would often exchange with an ion of calcium in the rock, with the result that the strontium ion would remain fixed while the calcium ion would move on with the water. The strontium ion would eventually get back into solution, but because of continual holdups of this type the radioactive strontium would move 100 times slower than the water, thus taking perhaps 100,000 years to reach the surface. For the other important waste components the holdup is even longer.



IF ALL WASTES WERE TO BE INGESTED, the biological effects on the human population of the U.S. would be considerable. As this graph shows, the number of cancer-causing doses in the wastes produced by one year of all-nuclear electric power in the U.S. is such that if all the wastes, after aging for 10,000 years, were to be converted into digestible form and fed to people, one would expect a million fatal cancers to ensue (*scale at left*). If instead the wastes were to be converted into soluble form and immediately after reprocessing dumped at random into rivers throughout the U.S., the result could again be a million fatalities (*scale at right*).

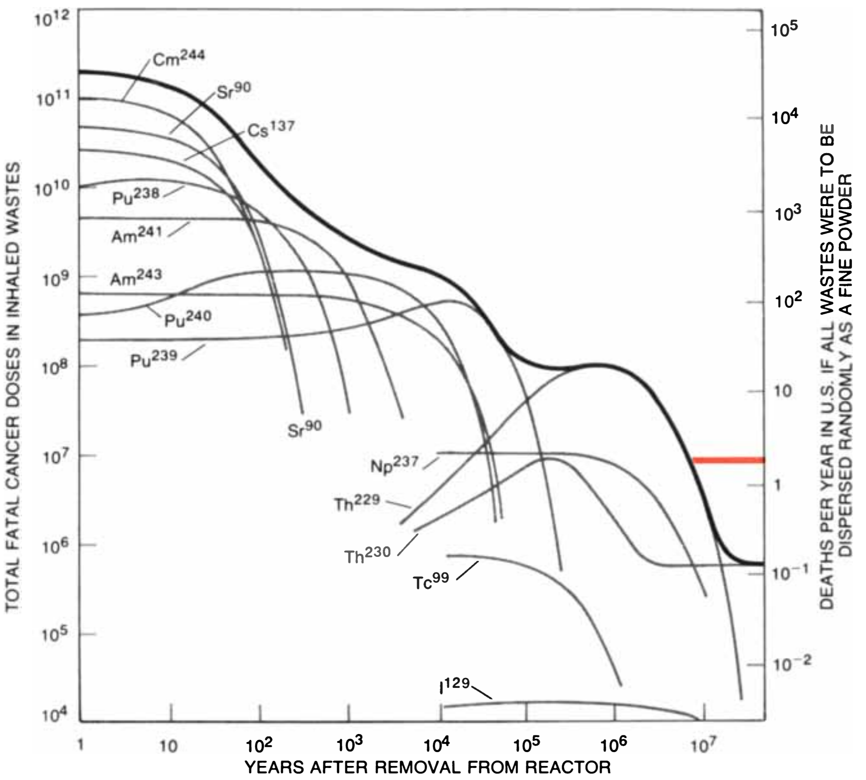
As a result of all these delays there is an extremely high assurance that very little of the wastes will escape through the ground-water route during the first few hundred years when they are most dangerous. Indeed, the time delays offer substantial protection for hundreds of thousands of years. I shall give no credit for this factor, however, in the following discussion of the potential longer-term hazard.

As we have seen, the "50 percent lethal" dose of nuclear wastes ingested after 600 years would be half a pound. This is hardly a potent poison, and its dangers seem particularly remote when one considers that the material is carefully buried in low-leachability form isolated from ground water a third of a mile below the earth's surface. Many more potent poisons are routinely kept in the home. It is true, however, that nuclear wastes remain poisonous for a very long time, so that they could conceivably present a hazard.

To evaluate this long-term risk one must develop an estimate of the probability that the wastes will escape into the environment. How can this be done? One way is to make a comparison between an atom of nuclear waste buried at a depth of 600 meters and a typical atom of radium somewhere in the rock or soil above the waste canister, assuming that the waste atom is no more likely than the radium atom to escape and find its way into a human being. This would seem to be a conservative assumption, since "the rock or soil above the waste canister" includes the material near the surface, where the erosive forces of wind, surface runoff, freeze-thaw cycles, vegetation and so on are active.

It is difficult to calculate the escape probability for an atom of radium in a particular area, but the average escape probability over the entire continental U.S. can be estimated. To make such a comparison meaningful one can assume that the wastes are buried in a uniform distribution over the entire country, but for calculating averages it is equivalent to assume that they are buried at random locations across the country and always at the same depth. When the assumption is stated this way, it is clearly conservative; one would think that by making use of all the information available from geology, hydrology and lithology one could choose a burial site that would be much securer than a randomly chosen one.

Having made these two basic assumptions—random burial and an equal escape probability for atoms of waste and radium—one need only estimate the average probability that an atom of radium in the top 600 meters of the U.S. will escape. One approach has two steps: calculating the probability that a radium atom will escape from the soil into rivers and multiplying this number by the probability that a given sample of water will be ingested by a human being. The average concentration of radium in rivers (two grams per 10 trillion liters) and the total annual water flow in U.S. rivers (1.5 quadrillion liters) are known quantities; the annual transfer of radium



IF ALL WASTES WERE TO BE INHALED, the most important health hazard would be the induction of lung cancers. In this graph again the scale at left shows the total number of cancer-causing doses in the wastes produced by one year of all-nuclear electric power in the U.S. The scale at right shows the number of deaths expected by the inhalation route if all these wastes were to be spread as a fine powder randomly over the ground throughout the U.S. In both this graph and the one on the opposite page the short colored line at the lower right indicates the corresponding long-term health hazard represented by the natural radioactivity in the uranium ore that would be consumed by such an all-nuclear electric-power system in the U.S.

from the soil into rivers is the product of these two numbers, or 300 grams. Since radium is a product of the radioactive decay of uranium, from the average concentration of uranium in rock (2.7 parts per million) one can readily estimate the amount of radium in the top 600 meters of the U.S. as being 12 billion grams. The annual transfer probability is the ratio of the annual transfer to the total quantity, or .000000025 per year. The inverse of this number, 40 million years, is then the average lifetime of rock in the top 600 meters of the U.S. Therefore the assumption is that each atom of buried nuclear waste has less than one chance in 40 million of escaping each year. About one part in 10,000 of river flow in the U.S. is ingested by human beings, but owing to various purification processes the fraction of the radium in river flow that is ingested is closer to 1.5 part in 100,000. Multiplying this number by the annual probability for escape into rivers (.000000025), one finally obtains the total annual transfer probability of a radium atom from the rock into a human being. It is roughly four chances in 10 trillion.

There are at least two flaws in this calculation. It ignores transfer through food, a factor that reduces the transfer probability, and it assumes that all the radium ingested is taken up by the body, a factor that increases the transfer probability. These problems can be avoided and the calculation can be simplified by estimating the number of human cancers induced annually by ingested radium (12) and dividing that number by the number of cancer-causing doses of radium in the top 600 meters of the U.S. (30 trillion). The first quantity is obtained from actual measurements of the amount of radium in cadavers combined with generally accepted estimates of the risk of a person's getting cancer from the radium. The result for the annual transfer probability obtained by this method is in close agreement with the figure derived by the preceding method. It therefore is reasonable to multiply the dosage scale in the ingestion graph on the opposite page by .0000000000004 (four chances in 10 trillion) to obtain the number of fatalities expected annually from the nuclear wastes produced annually by an all-nuclear U.S. electric-power system.

What all of this means is that after the first few hundred years of storage, during which we would be protected by the time delays discussed above, one could expect about .000001 fatality per year or less attributable to the buried waste. When this toll is added up, it comes to .4 fatality for the first million years plus an additional four fatalities over the next 100 million years.

If one is to consider the public-health effects of radioactivity over such long periods, one should also take into account the fact that nuclear power burns up uranium, the principal source of radiation exposure for human beings today. For example, the uranium in the ground under the U.S. is the source of the radium that causes 12 fatal cancers in the U.S. per year. If it is assumed that the original uranium was buried as securely as the waste would presumably be, its eventual health effects would be greater than those of the buried wastes. In other words, after a million years or so more lives would be saved by uranium consumption per year than would be lost to radioactive waste per year.

The fact is, however, that the uranium now being mined comes not from an average depth of 600 meters but from quite near the surface. There it is a source of radon, a highly radioactive gaseous product of the decay of radium that can escape into the atmosphere. Radon gas is the most serious source of radiation in the environment, claiming thousands of lives in the U.S. per year according to the methods of calculation used here. When this additional factor is taken into account, burning up uranium in reactors turns out to save about 50 lives per million years for each year of all-nuclear electric power in the U.S., more than 100 times more than the .4 life that might be lost to buried radioactive wastes.

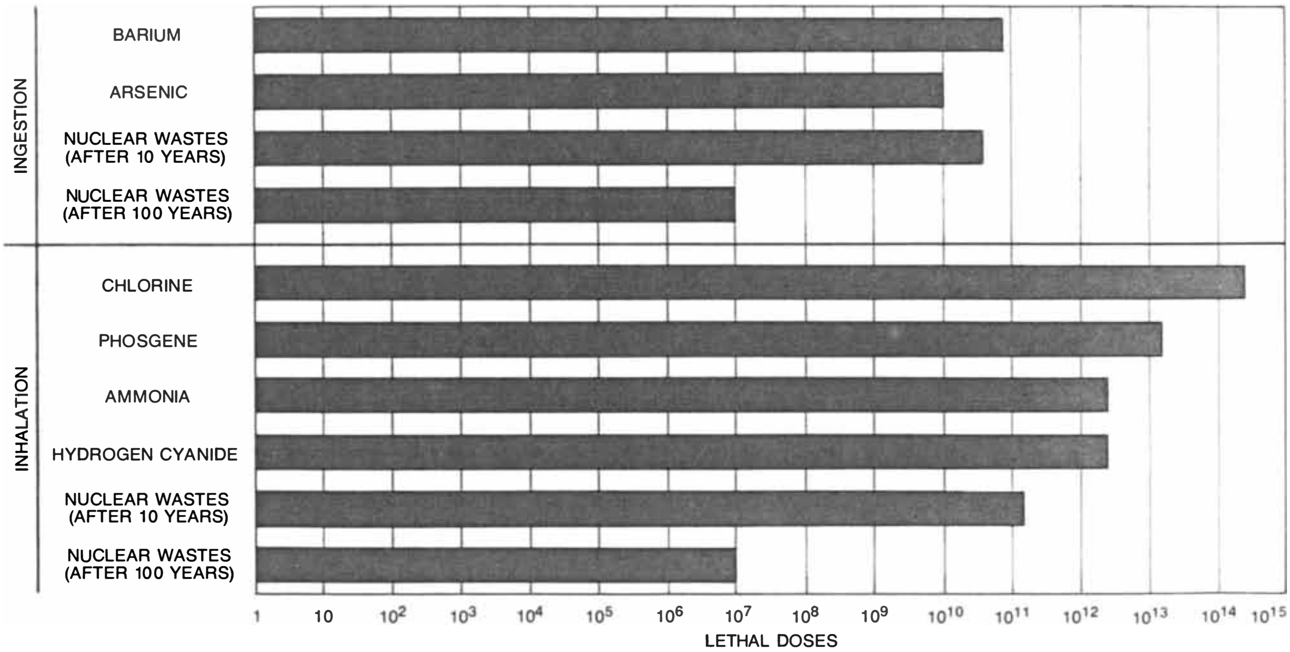
Thus on any long time scale nuclear power must be viewed as a means of cleansing the earth of radioactivity. This fact becomes intuitively clear when one considers that every atom of uranium is destined eventually to decay with the emission of eight alpha particles (helium nuclei), four of them rapidly following the formation of radon gas. Through the breathing process nature has provided an easy pathway for radon to gain entry into the human body. In nuclear reactors the uranium atom is converted into two fission-product atoms, which decay only by the emission of a beta ray (an electron) and in some cases a gamma ray. Roughly 87 percent of these emission processes take place before the material even leaves the reactor; moreover, beta rays and gamma rays are typically 100 times less damaging than alpha-particle emissions, because their energies are lower (typically by a factor of 10) and they deposit their energy in tissue in less concentrated form, making their biological effectiveness 10 times lower. The long-term effect of burning uranium in reactors is hence a reduction in the health hazards attributable to radioactivity.

In this connection it is interesting to note that coal contains an average of about 1.5 parts per million of uranium, which is released into the environment when the coal is burned. The radon gas from the uranium released by one year of an all-coal-powered U.S. electric-generating system would cause about 1,000 fatalities per million years, a rate three orders of magnitude greater than the result obtained above for the wastes from an all-nuclear-powered system.

If the risk of ingesting radioactive waste materials with food or water is so low, what about the risk of inhaling them as airborne particulate matter? The potential hazards from inhaling such materials are much greater and longer-lasting than the hazards from ingesting them. It is difficult, however, to imagine how buried nuclear wastes could be released as airborne particulates. The largest nuclear bombs yet considered would not disturb material at a depth of 600 meters. Meteorites of sufficient size to do so are extremely rare, so that their average expected effect would be a million times lower than that from ingestion. Volcanic eruptions in tectonically quiet regions are also extremely rare; moreover, they disturb comparatively small areas, so that their effects would be still smaller.

Release through ground water could lead to a small fraction of the radioactivity being dispersed at the surface in suspendable form, but calculation indicates that for this pathway to be as hazardous as ingestion all the wastes would have to be dispersed through it. Wastes dispersed at the surface would also constitute an external-radiation hazard through their emission of gamma rays, but another calculation demonstrates that this hazard too is less than that of ingestion.

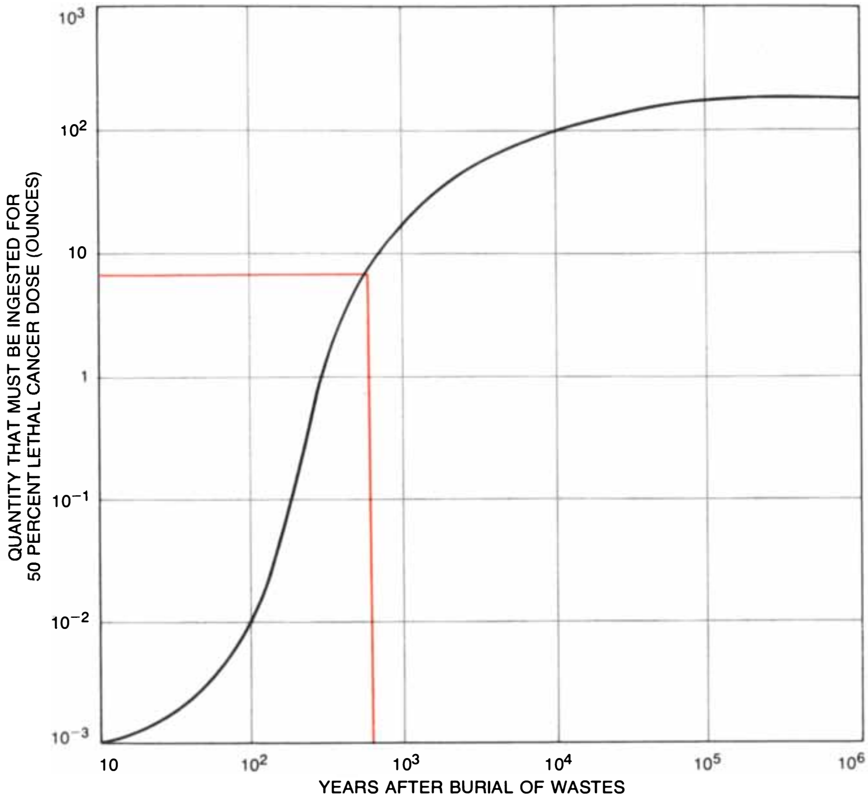
None of the estimates I have given so far takes into account the possible release of nuclear wastes through human intrusion. Let us therefore consider that



COMPARISON OF HEALTH HAZARDS presented by high-level radioactive wastes from nuclear reactors with those of other poisonous substances routinely used in large quantities in the U.S. demonstrates that there is nothing uniquely dangerous about the nuclear wastes. Moreover, the author notes, "chemical poisons are not carefully buried deep underground as is the plan for the nuclear wastes; indeed, much of the arsenic is used as a herbicide and hence is routinely scattered around on the ground in regions where food is grown."

possibility. Buried waste would not be an attractive target for saboteurs because of the great amount of time, effort, equipment and personal danger that would be needed to remove it. Only release through inadvertent human intrusion, such as drilling or mining, needs to be considered. The current plan is to retain Government ownership of repository sites and to maintain surveillance and long-lasting warning signs, so that this problem would exist only if there were a total collapse of civilization. One of the criteria for the choice of a repository site is that there be a lack of valuable minerals and the prospect of discovering them. (Indeed, the principal factor delaying the development of the proposed New Mexico site is the possibility that it may hold potash deposits.) Nevertheless, if there were random exploratory drilling in the area at the rate of the current average "wildcat" drilling for oil in the U.S., the effects would still be much less than those of release in ground water. If there were mining in the area (presumably for minerals not now regarded as valuable), the operations would have to be on a scale approaching that of the entire current U.S. coal-mining enterprise before their effects would equal those of ground-water release.

Wastes buried in salt might seem to be a poor risk against the possibility of intrusion by mining, since salt is widely mined. The quantity of salt underground, however, is so huge that on a random basis any given area would not be mined for tens of millions of years. Again the probability of release through this pathway is comparable to that through ground water, except that here the wastes are in insoluble form and, if ingested, much less likely to be taken up by the body. A pathway would seem to exist through the use of salt in food, but only 1 percent of the salt mined in the U.S. is so used, and it is purified by allowing insoluble components to settle out. Thus exposure through this pathway would be reduced roughly to that through the use of salt in industrial processes. All in all, then, the probability of the release of stored nuclear wastes through human intrusion is less than that of their release through ground water.



DANGER FROM INGESTED WASTES can be shown to be very great at first but much less after a few hundred years. As this graph shows, after 600 years a person would have to ingest approximately half a pound of the buried wastes to incur a 50 percent chance of contracting a fatal cancer. Such a calculation suggests that although it is obviously very important to isolate such wastes from human contact for a few hundred years, it is less imperative thereafter.

It is often said that by producing radioactive wastes our generation places an unjustifiable burden on future generations in requiring them to guard against their release. Here it should first be recognized that the estimate of the health effects of nuclear wastes I have given—an eventual .4 fatality for each year of all-nuclear power—was based on no guarding at all. The estimate was derived from a comparison with radium, and no one is watching this country's radium deposits to prevent them from getting into rivers through various earth-moving operations. Therefore guarding buried nuclear wastes would only serve to reduce that already small toll.

Even if guarding should be considered advisable, it would not be very expensive or difficult. Once the repository is sealed the guarding would consist only in making periodic inspections of the surface area—about 10 miles square for the wastes from 1,000 years of all-nuclear power—to make sure that the warning signs are in good order and to see that no one has unexpectedly undertaken mining or deep drilling. In addition occasional water samples might be drawn from nearby rivers and wells to check for increased radioactivity. Hence keeping watch on the wastes accumulated over 1,000 years of all-nuclear electric power in the U.S. would provide a job for only one person at a time.

Perhaps the best way to put into perspective the burden we are placing on our descendants by storing nuclear wastes is to compare that burden with others we are placing on them. Probably the worst will be the burden resulting from our consumption of the earth's high-grade mineral resources. Within a few generations we shall have used up all the world's economically recoverable copper, tin, zinc, mercury, lead and dozens of other elements, leaving fewer options for our descendants to exploit for materials. Moreover, we are burning hydrocarbons—coal, oil and gas—at the rate of millions of tons each per day, depriving our descendants not only of fuels but also of feedstocks for making plastics, organic chemicals, pharmaceuticals and other useful products. These burdens are surely far heavier than any conceivable burden resulting from the appropriate burial of nuclear wastes.

What makes this comparison particularly pertinent is that the only way we can compensate our descendants for the materials we are denying them is to leave them with a technology that will enable them to live in reasonable comfort without these materials. The key to such a technology must be cheap and abundant energy. With cheap and abundant energy and a reasonable degree of inventiveness man can find substitutes for nearly anything: virtually unlimited quantities of iron and aluminum for metals, hydrogen for fuels and so on. Without cheap and abundant energy the options are much narrower and must surely lead back to a quite primitive existence. It seems clear that we who are alive today owe our descendants a source of cheap and abundant energy. The only such source we can now guarantee is nuclear fission.

The Uses of Synchrotron Radiation

Electrons traveling in a circular orbit at nearly the speed of light emit intense radiation at ultraviolet and X-ray wavelengths. Such radiation provides unmatched illumination for the study of matter

by Ednor M. Rowe and John H. Weaver

When Newton conducted his famous prism experiment in 1666, the entire known spectrum consisted of the narrow band of wavelengths perceived as visible light. Today the known electromagnetic spectrum is many orders of magnitude wider, extending from low-frequency radio waves to extremely energetic gamma rays. What is more, the experimenter is no longer dependent, as Newton was, on natural sources of radiation. Almost any wavelength can be generated at will in the laboratory. For visible wavelengths and for nearby regions in the infrared and the ultraviolet there are incandescent sources, such as the ordinary light bulb, gas-discharge tubes and the laser. Radio-frequency waves are generated with great facility and flexibility by electronic devices. Gamma rays are created by the collisions that take place in particle accelerators and are also emitted in the radioactive decays of some atomic nuclei.

There remains one region of the electromagnetic spectrum where the conventional laboratory sources are inadequate. It extends from frequencies just above those of visible light through the ultraviolet and X-ray portions of the spectrum to the frequencies of low-energy gamma rays. Wavelengths within this broad range have the same dimensions as characteristic structures in atoms, molecules and solids. As a result the interaction of the electromagnetic radiation and matter is exceptionally strong. Radiation in this range, if it were conveniently available, would serve as an excellent probe of the structure of matter.

In the past 10 years or so a new source of electromagnetic radiation has become available that fills the gap almost ideally. It is the radiation emitted by electrons when they are made to follow a circular path at a speed near the speed of light. The phenomenon has been given the name synchrotron radiation because it was first observed at visual wavelengths in particle accelerators of the synchrotron type. So far most experiments employing synchrotron radiation have been conducted with machines designed mainly for experiments in nuclear physics and the physics of elementary particles. There are now several proposals to build machines dedicated to the production of synchrotron radiation; they would be particle accelerators operated as light bulbs.

In the visible part of the spectrum electromagnetic radiation is generated mainly by incandescent solids and by excited electrons in hot gases. The light emitted by gases consists of discrete bright lines, each with a particular wavelength that cannot readily be adjusted. The light is emitted when an electron falls from an excited state to a state of lower energy; the energy of the emitted radiation is equal to the difference in energy between the two states. Energy, of course, is inversely related to wavelength: the greater the energy of a photon, or quantum of light, the shorter the wavelength of the associated wave. The energy is customarily measured in electron volts; an electron volt is defined as the energy acquired by an electron when it is accelerated through a potential difference of one volt.

Visible light is ordinarily emitted by transitions involving the valence, or outermost, electrons of atoms. Those electrons are strongly influenced by their immediate environment, and their energy levels are much disturbed when a rarefied gas condenses to form a solid. In principle the valence electrons still have discrete, quantized energy levels, but the levels are smeared out into broad bands by the proximity of many atoms. In a solid it is not possible to distinguish individual energy levels or the sharp line spectrum associated with transitions between them. Instead the emitted spectrum is a continuum: it has a peak intensity at some wavelength, but energy is also radiated at all other nearby wavelengths. For an ideal radiating solid the distribution of wavelengths has the characteristic shape called a black-body spectrum.

For the experimenter a continuous spectrum has some rather obvious advantages. Observations are no longer confined to those wavelengths that happen to correspond to an available emission line but can be made at any desired wavelength.

The wavelength of peak emission in the black-body spectrum is determined primarily by temperature. Increasing the temperature shifts the peak to shorter wavelengths. As a practical matter, however, the peak intensity cannot be pushed to wavelengths much shorter than those of red or yellow light because the required temperature exceeds the boiling points of all solids. For example, a tungsten lamp filament operating at a temperature of 3,000 degrees Kelvin radiates most intensely at a wavelength of about 9,000 angstroms. The visible spectrum extends from roughly 4,000 angstroms (violet) to 7,000 angstroms (red), so that 9,000 angstroms lies in the infrared region. The peak in the black-body spectrum could be shifted to 3,000 angstroms, in the near ultraviolet, by heating the filament to 10,000 degrees K. Metallic tungsten melts, however, at 3,410 degrees K., and it boils at 5,927 degrees K.

Because of temperature limitations on the black-body spectrum, radiation sources in the ultraviolet have traditionally been gas-discharge lamps. The major part of the radiation from these sources is emitted in discrete spectral lines. At X-ray wavelengths it is possible to return to solid-state sources, but these sources also provide mostly line emission, with only a weak continuum. The X rays are generated by exciting not the valence electrons but electrons in inner shells. These core electrons are tightly bound and emit sharp lines as if they were isolated, like the outer-shell electrons in the atoms of a gas.

Electromagnetic radiation arises ultimately from the acceleration of electric charges. That is the meaning of the field equations describing electromagnetism that were formulated in the 19th century by James Clerk Maxwell.

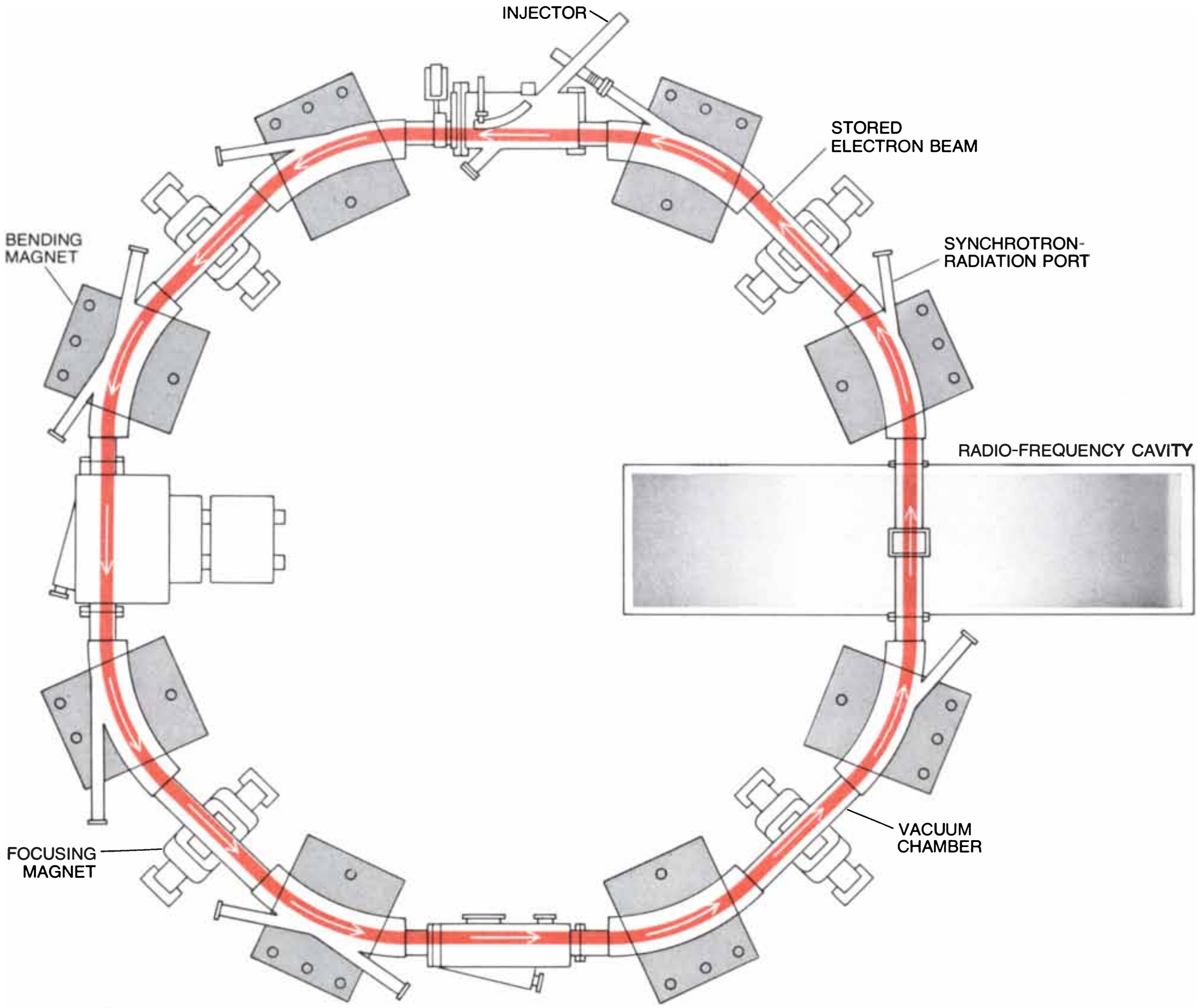
In almost all instances the charges accelerated are electrons, since they are by far the lightest charged particles and therefore the most easily accelerated.

An example of an accelerated charge is a single electron oscillating in a straight line with sinusoidally varying speed, somewhat like the bob of a long pendulum or a weight suspended from a spring. In each full cycle the electron is accelerated and decelerated twice, and as a result it radiates an electromagnetic wave that is propagated away from the particle. The radiation has a characteristic frequency, equal to the electron's frequency of oscillation. Harmonics, or multiples, of this fundamental frequency can also be detected. The radiation also has a characteristic spatial pattern: it is most intense in the plane perpendicular to the axis along which the electron oscillates, and it falls to zero along that axis. In a klystron tube, a generator of microwave radiation, electrons describe just such sinusoidal motions.

Transitions between the energy states of electrons in atoms also involve the acceleration of charges, although it is not usual to regard them in that way. The acceleration can readily be imagined in a simplistic, planetary model of the atom, since an electron moving from one orbit to another must change its orbital velocity. Such a model is a useful descriptive device, but for a quantitative treatment of atomic spectra a more sophisticated, quantum-mechanical model would be needed. Indeed, quantum mechanics is required even to explain why the electron shells of atoms are stable and why the electrons do not radiate away all their energy.

The connection between acceleration and radiation is more obvious in the spectrum emitted by some X-ray tubes. Such tubes operate by accelerating electrons to high energy and then allowing them to strike a metallic electrode. Within the electrode the motions of the electrons are influenced by the strong fields of the atomic nuclei, and the electrons are slowed or even stopped within small distances. In other words, the electrons are violently decelerated. The resulting radiation has been given the name bremsstrahlung, meaning (in German) "braking radiation."

The bremsstrahlung spectrum is a continuum within its range of wavelengths, but significant intensity can be



ELECTRON STORAGE RING called Tantalus I is operated as a source of synchrotron radiation. The radiation is generated when electrons moving at a speed near the speed of light are made to follow a circular path; in Tantalus that happens in each of the bending magnets, where the electron orbits describe arcs of a circle. The electrons are introduced into the storage ring through the injector at the top; once they have been accelerated to the operating energy of the ring they can be stored in an essentially constant orbit for many hours. Energy lost through radiation is restored to the electrons in the radio-frequency cavity. The synchrotron radiation is emitted in a narrow beam tangent to the electron orbit, and the ports for experiments employing the radiation are therefore tangent to the main ring.

achieved only at energies greater than about 10,000 electron volts (or, equivalently, at wavelengths less than one angstrom). Thus bremsstrahlung does not provide a continuum source for the ultraviolet or for the lower-energy X rays. Moreover, electrons striking an electrode at such high energies commonly excite the innermost core electrons of the metal atoms, which then return to the ground state by emitting an X-ray line spectrum in the same wavelength range as that of the bremsstrahlung. As a result the radiation is contaminated with discrete lines many times brighter than the continuum.

An electron moving in a circular orbit with constant velocity has a particularly simple accelerated motion. This is the configuration of an electron emitting synchrotron radiation. The radiation was actually first detected not in particle accelerators but in astronomical observations. Electrons moving in the intense magnetic fields found in supernova remnants follow circular (or helical) paths and therefore radiate by the synchrotron mechanism. The terrestrial generation of the radiation, in a circular electron accelerator, was first investigated in the 1940's.

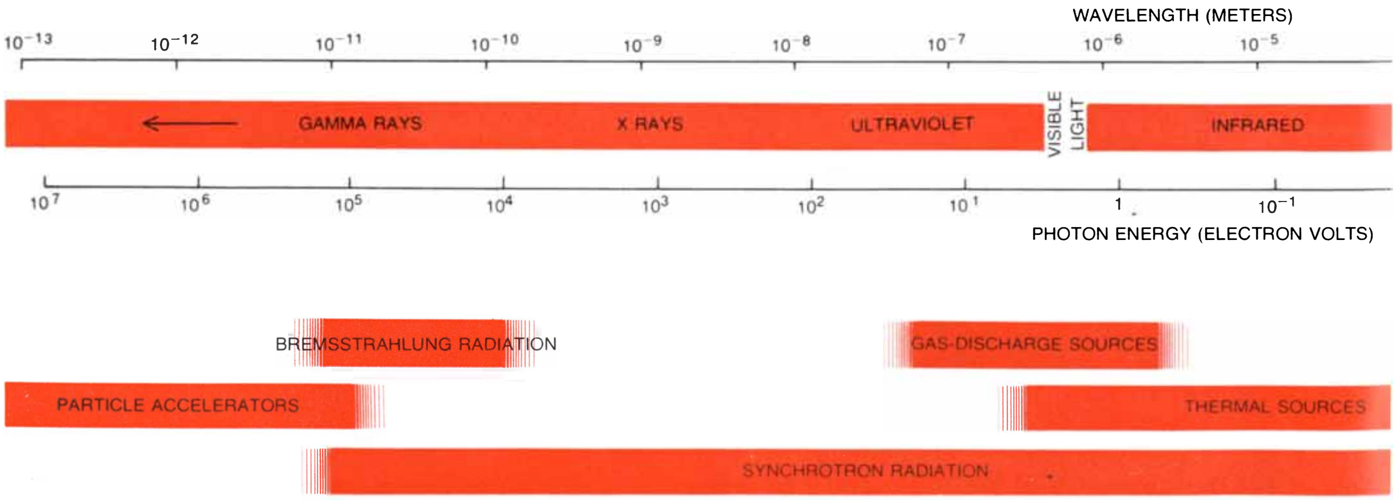
It should be emphasized that an acceleration is any change in velocity, and that velocity defines not only speed but also direction of motion. Therefore a particle in a circular orbit is subject to a continuous centripetal acceleration. If the dimensions of the orbit are stable and the orbital velocity is constant, then the acceleration is also constant. The electron radiates continuously.

The radiation pattern for such a circulating charge was first deduced by the British mathematician and physicist Sir Joseph Larmor. He showed that for an observer who is moving in the orbiting electron's frame of reference (and hence who is orbiting with it) the radiation is most intense in the plane tangent to the electron orbit. The intensity falls to zero in those directions parallel to radii of the electron orbit. Thus the radiation pattern has the shape of a rather fat tire rolling around the electron orbit on an axle that corresponds to a radius of the orbit.

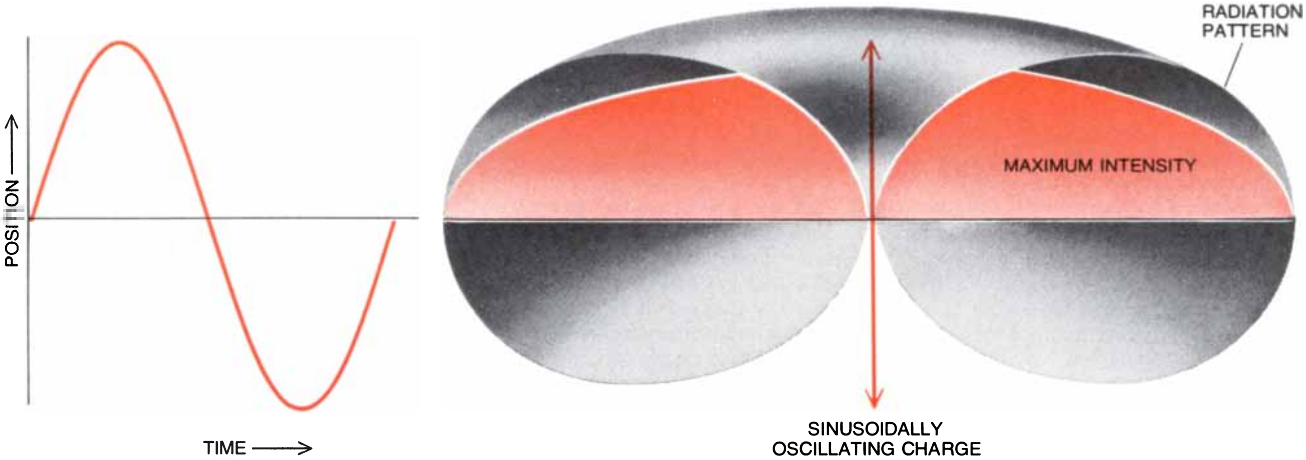
For an observer who is not moving with the electron but who sees it from the laboratory frame of reference, the radiation pattern changes little as long as the orbital speed is modest. At low electron speeds relativistic effects cause only a modest foreshortening, diminishing the intensity of radiation emitted in the rearward direction and increasing the forward radiation.

The Larmor pattern is transformed altogether, however, as the speed of the circulating electron approaches the speed of light. For an observer in the laboratory frame of reference, radiation to the rear and to the sides of the electron falls away completely, and all the radiation is concentrated in a forward-facing cone. As the electron's speed approaches the speed of light that cone becomes very narrow. The half angle (formed by the axis tangent to the electron orbit and the side of the cone) is given very nearly by the expression $\sqrt{1 - v^2/c^2}$, where v is the speed of the electron and c is the speed of light. If v could equal c, the opening angle of the cone would be zero and all the radiation would be emitted on the tangent. Attainable values of the angle can be quite small. For electrons with an energy of 240 MeV (million electron volts), a quite plausible energy for a synchrotron, v is .9999975 the speed of light. Substituting this value in the expression above, we find that the cone of radiation diverges by only about .1 degree. It follows from these calculations that an electron in a circular orbit sheds radiation tangentially in much the same way that mud is slung off a spinning tire. The radiation is emitted throughout the circumference of the orbit, but only within a narrow vertical angle centered on the orbital plane. As viewed by an observer looking at the electron beam within this plane, the radiation is a bright spot, of approximately the same cross-section as the electron beam, where his line of sight is tangent to the orbit and where the electrons are momentarily moving directly toward him.

Just as the spatial pattern of synchrotron radiation changes as the orbiting electron becomes relativistic, so too the spectral distribution of the radiation is altered. At low speeds the electron radiates mainly at its orbital frequency, in the same way that a sinusoidally oscillating electron radiates at its frequency of oscillation. In an orbit of fixed circumference the frequency itself increases as the electron moves faster, but at the electron energies of interest the fundamental frequency is essentially constant. What does change significantly as the energy increases is the apportionment of the radiated energy between the fundamental frequency and the various harmonics of that frequency. At low speed almost all the energy is radiated at the fundamental frequency (the frequency of revolution). As the electron speed approaches c more and more energy goes into higher harmonics. The order of magnitude of the highest harmonic frequency radiating significant energy is given by $(1/\sqrt{1 - v^2/c^2})^3$. This parameter becomes very large as v approaches c. For electrons with an



ELECTROMAGNETIC SPECTRUM describes radiation according to its wavelength or, in an alternative representation, according to the energy of photons, the quanta of electromagnetic radiation. Wavelength and photon energy are inversely related. No single source of radiation covers the entire spectrum; most sources are effective only over a narrow range. Synchrotron radiation is available at signif-



EMISSION OF RADIATION invariably results from the acceleration of an electric charge; the charge is almost always an electron, the lightest and most easily accelerated charged particle. An example is an electron in sinusoidal oscillatory motion along a straight line, as in the graph at the left. Such an electron radiates in a characteristic pattern with peak intensity in the plane perpendicular to the axis of oscillation and with no emission along that axis. The fundamental frequency of the radiation is equal to the frequency of oscillation.

energy of 240 MeV and a velocity of .9999975c it is roughly 10^8. A relativistic electron in a circular orbit with a circumference of 10 meters would have a fundamental frequency of revolution of about 10^7 hertz, in the radio region of the electromagnetic spectrum. The 10^8th harmonic of that frequency is 10^{15} hertz, which corresponds to a wavelength in the ultraviolet.

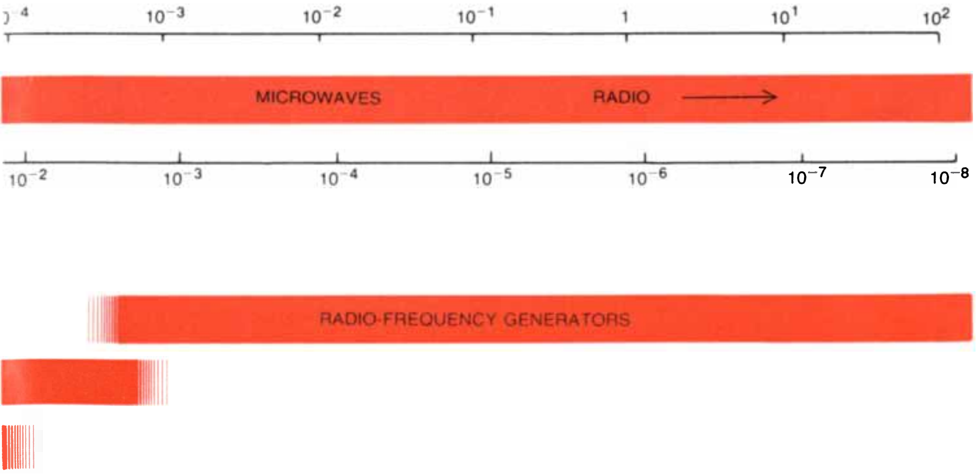
In a formal sense the synchrotron-radiation spectrum of a single electron consists of a great many discrete frequencies: the harmonic series based on the fundamental frequency of revolution. Actually it is a true continuum. The higher harmonics of any frequency are very closely spaced. Since no spectral line can be infinitely sharp and narrow, the lines blur together. As the speed of the electron approaches that of light the synchrotron spectrum becomes a broad, continuous band with its peak intensity at a frequency far above the fundamental frequency of rotation. The harmonic content of the radiation becomes strong first in the visible, then in the ultraviolet and finally in the X-ray region of the electromagnetic spectrum.

For an electron moving in a circular orbit the total energy lost to synchrotron radiation is proportional to the expression $(1/\sqrt{1 - v^2/c^2})^4$, which implies that the radiation losses increase as the fourth power of the electron energy. Raising the energy of the electrons by a factor of 10 increases the energy radiated roughly 10,000 times. The loss is a handicap for the physicist interested in maintaining electrons in a circular particle accelerator. That loss, however, also represents an unmatched source of high-intensity, tunable radiation.

Two kinds of machine make suitable sources of synchrotron radiation: electron synchrotrons and electron storage rings. Both devices consist of a toroidal vacuum chamber surrounded by various bending and focusing magnets and including cavities for the injection of radio-frequency energy. The circular electron orbit is maintained by the magnets; at any point the orbit's radius of curvature is inversely proportional to the strength of the magnetic field.

In the synchrotron a "bunch," or pulse, of electrons is injected into the vacuum chamber and then accelerated over the course of many revolutions to some maximum energy. The acceleration is effected by radio-frequency energy supplied through a resonant cavity or through several cavities that make up part of the vacuum chamber. As the speed of the electrons increases, the magnetic field must also be increased smoothly, in synchrony with the acceleration; hence the name synchrotron. Finally, when the electrons have attained their terminal energy, they are extracted from the machine.

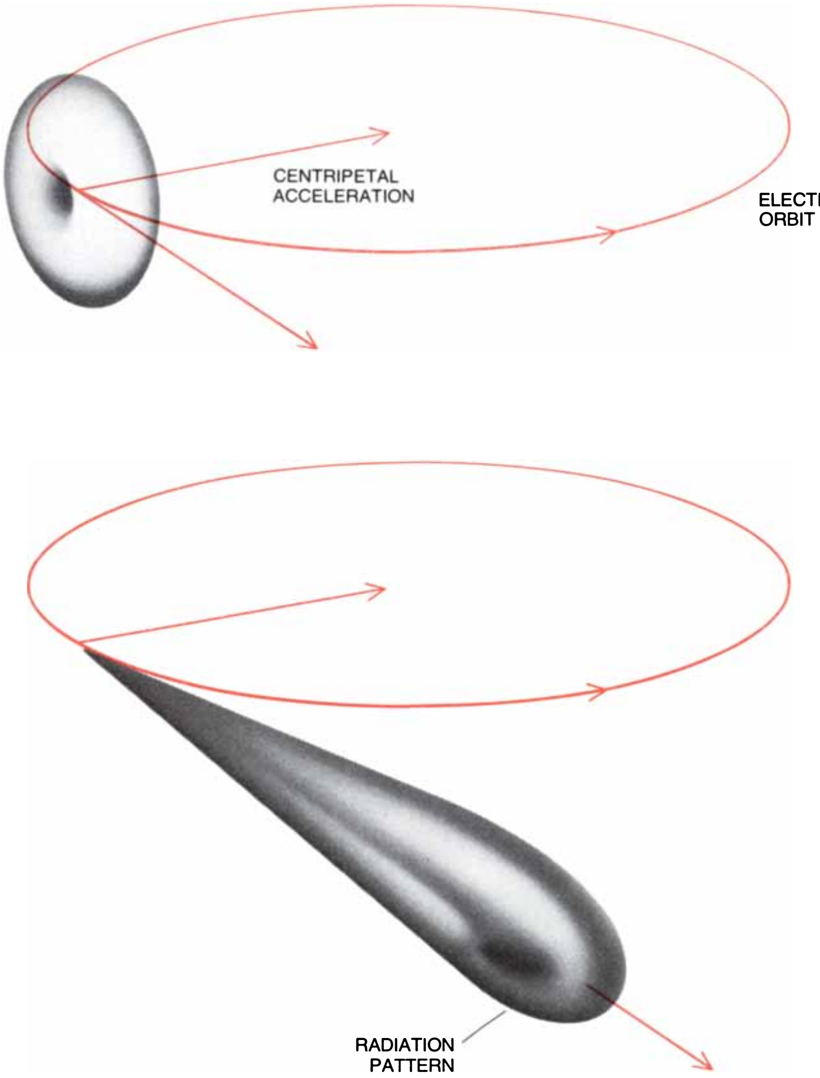
An electron storage ring is similar in both construction and operation. Electrons are injected into the toroidal vacuum chamber and confined to a circular orbit by bending magnets. The main difference is that the electrons are not extracted after a cycle of acceleration; instead they are made to circulate at a constant energy, often for many hours. An energy source in the form of a radio-frequency cavity is still required, but only to make up for the energy lost as synchrotron radiation. Some storage rings receive electrons at high energy from an external accelerator. In others the electrons are injected at low energy and the ring is operated briefly as a synchrotron in order to accelerate them. In either case once the beam is established



icant intensity from wavelengths longer than those of visible light through the ultraviolet and X-ray regions of the spectrum. Over much of this range it is the only source of radiation that provides a continuous spectrum (rather than discrete wavelengths with dark bands in between).

the electrons can occupy a stable orbit almost indefinitely. Their velocity is maintained by small increments of electromagnetic energy supplied with each revolution. The orbit is defined by the bending magnets and the beam is prevented from dispersing by focusing magnets. The electrons circle the ring in bunches a few centimeters long; the ring may be operated with a single bunch of electrons or with several bunches.

For generating synchrotron radiation, storage rings have a number of advantages over synchrotrons. In the synchrotron the spectrum of the radiation changes with each revolution as a bunch of electrons gains energy. The position of the bunch within the beam tube—and hence the position of the radiating spot—can also vary during the acceleration cycle. In a storage ring, on the other hand, both the spectrum and the position of the beam are constant (although they can be adjusted if need be). For a storage ring the spectral distribution and the intensity of the synchrotron radiation can be calculated directly if three factors are known: the number of electrons stored, their energy and the radius of curvature of the orbit. The beam in a storage ring is stable enough and its characteristics are sufficiently well understood for synchrotron radiation to be employed as a standard for calibrating other sources of radiation and detectors of it.



ELECTRON IN A CIRCULAR ORBIT has a continuous centripetal acceleration, and it therefore radiates continuously. At a comparatively low orbital speed (substantially lower than the speed of light) the radiation pattern resembles a torus centered on the electron with the plane of maximum intensity tangent to the electron orbit (*top*). As the orbital speed increases, the radiation pattern becomes progressively more distorted. As the speed of the electron approaches the speed of light all the radiation is confined to a narrow cone tangent to the orbit (*bottom*). The frequency of the radiation changes along with the pattern. At low speed it is equal to the rotation frequency; at relativistic speed the radiant energy is distributed among many higher harmonics of the rotation frequency and the spectrum is essentially a continuum.

Whether it is generated by a synchrotron or by a storage ring, synchrotron radiation has several properties that make it particularly desirable as a source of illumination. The principal advantage, of course, is the high intensity of the emitted radiation over a broad range of wavelengths. A useful flux is available from the near infrared to "hard" X rays: those with wavelengths of less than an angstrom or so.

In many measurements where electromagnetic radiation is the probe it is desirable to polarize the radiation, so that all the waves in a beam have their electric fields oriented in the same direction. Uniform polarization eliminates ambiguity in the interpretation of some measurements and makes possible a greater variety of measurements. Synchrotron radiation is naturally polarized, with the electric field parallel to the plane of the electron orbit. The degree of polarization varies with wavelength and is a function of angle above or below the orbital plane. At the wavelength of peak intensity and in the orbital plane the radiation is virtually 100 percent polarized.

The fact that electrons in a storage ring circulate not as a continuous current but in small bunches also has an effect on synchrotron radiation, an effect that is often helpful to the experimenter. When it is viewed from any fixed point on the perimeter of the ring, the synchrotron radiation is not continuous but appears as a series of brief pulses. Each time the bunch of electrons passes, a burst of radiation is emitted; when the bunch is elsewhere in its orbit, no radiation is observed. For many experiments this pulsation is a convenience. In particular, excited states of atoms that decay in the brief dark period between bunches can be examined.

Another incidental convenience of employing an electron storage ring as a light source is ready access to an excellent vacuum. Successful operation of a storage ring requires an ultrahigh vacuum of 10^{-10} to 10^{-11} torr; any more gas present in the ring would scatter the stored electrons and thereby reduce the period during which a beam could be stored. The beam tubes carrying the synchrotron radiation to the experimental stations communicate with the ring and therefore must be maintained at the same vacuum. Since a good vacuum is required for many of the observations that can be made with synchrotron radiation, the specimen to be illuminated is often placed in an experimental chamber communicating with the vacuum system of the storage ring.

Synchrotron radiation has been known for only 30 years, and it has been employed extensively in research for only the past 10 years. The first successful application was made in 1963 by

Robert P. Madden and Keith Codling of the National Bureau of Standards. With the radiation from a 180-MeV electron synchrotron they were able to make unprecedented measurements of the absorption of low-energy X rays by gases.

More intense sources of synchrotron radiation have since become available. One of the earliest was at the German Electron Synchrotron in Hamburg, abbreviated as DESY. A storage ring at DESY is operated primarily for research in high-energy particle physics, and synchrotron radiation is available as a "free" by-product.

A similar arrangement exists at the Stanford Linear Accelerator Center, where synchrotron radiation is generated in the storage ring called SPEAR. The DESY and SPEAR rings actually store counterrotating beams of electrons and their antiparticles (positrons), but only the radiation from the electron beam is being utilized.

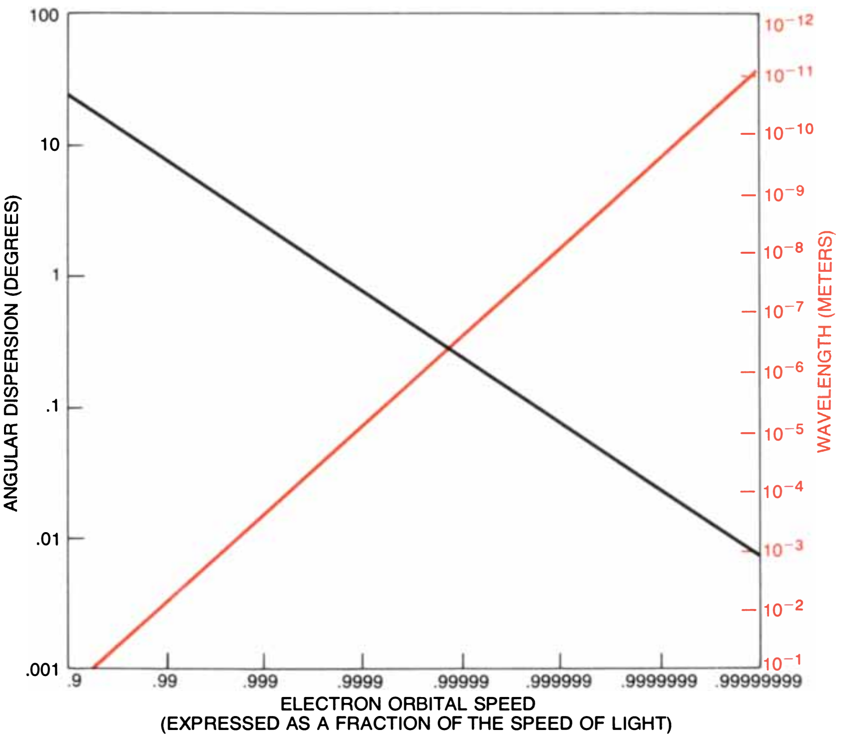
Until recently only one accelerator has been devoted exclusively to the generation of synchrotron radiation. It is Tantalus I, operated at the University of Wisconsin for the National Science Foundation. Tantalus I was designed for research on the technology of particle accelerators, but in 1966 it was proposed that the machine might better serve as a source of radiation for the spectroscopic study of solids and gases. The proposal was accepted, and the first synchrotron-radiation beam was produced in 1968.

Tantalus I is an electron storage ring with an operating energy of 240 MeV. Electrons are injected into the ring by a small accelerator, called a microtron, that gives them an initial energy of 40 MeV. The storage ring is then briefly operated as a synchrotron until the electrons reach their final energy.

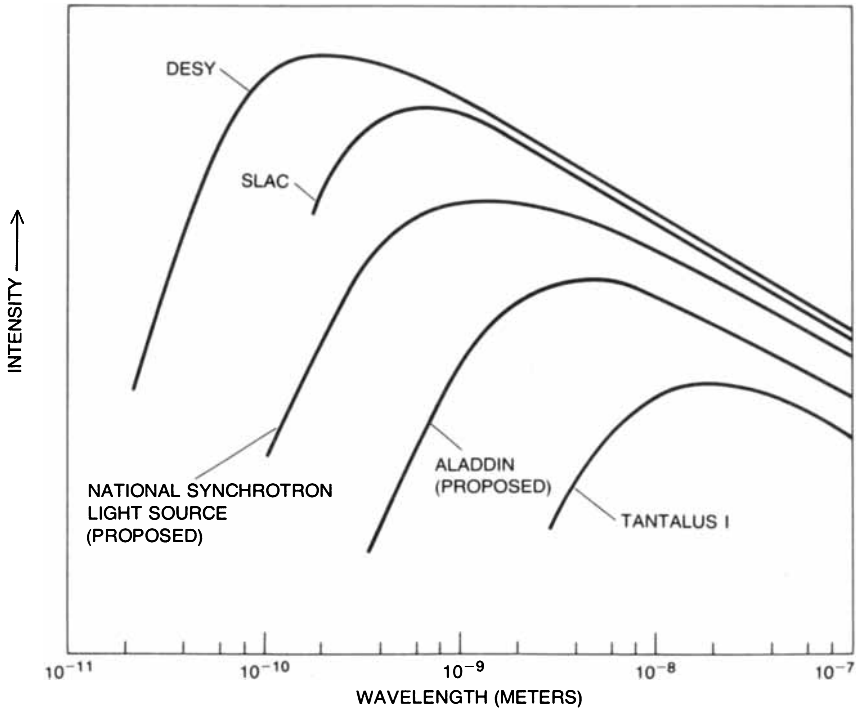
Tantalus I has nine ports where the synchrotron radiation is collected, and several of these radiation beam lines are split so that they can simultaneously serve more than one experiment. Each year about 40 groups of experimenters can be accommodated.

In a typical experiment synchrotron radiation emerges from an accelerator or storage ring through an evacuated pipe that joins the ring tangentially. Looking up this beam pipe while the accelerator is operating, one would see a bright spot, typically one or two millimeters in diameter, centered in the tube. That spot is an image of the electron beam at the point in its orbit where the tangentially emitted radiation happens to be swept across the port.

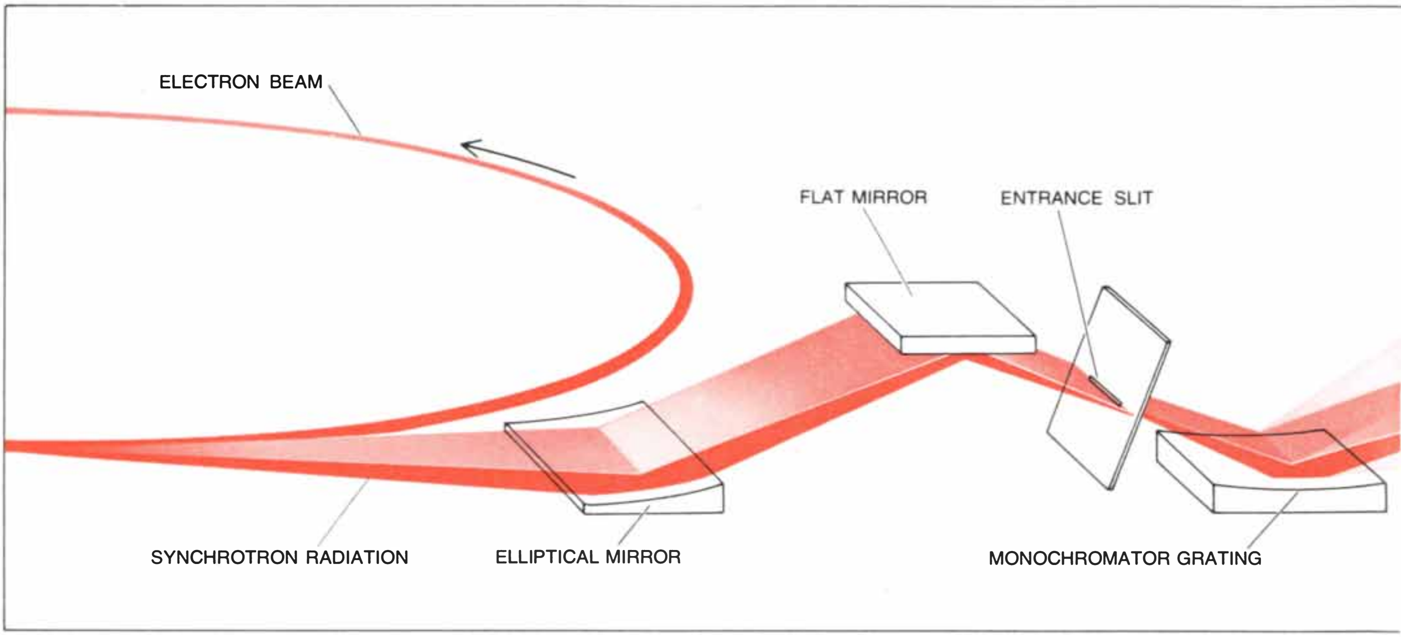
Synchrotron radiation is emitted in a rather narrow pencil, but in most experiments it is further collimated, and generally a narrow band of wavelengths is selected from the spectrum by a monochromator mounted at the end of the



WAVELENGTH AND ANGULAR DISTRIBUTION of synchrotron radiation change rapidly as the energy of the emitting electrons increases and as their speed approaches the speed of light. Speed is expressed here on a logarithmic scale as a fraction of the speed of light. The wavelengths indicated are the shortest wavelengths at which significant power is radiated for a given electron energy. The angular distribution of the radiation becomes narrower as the energy increases, and ultimately the radiation is a collimated pencil of almost parallel rays.



SOURCES of synchrotron radiation provide a continuous spectrum with maximum intensity at a wavelength determined by the energy of the accelerated electrons and the radius of curvature of the electron orbit. The highest electron energies and shortest wavelengths are available with the German Electron Synchrotron (DESY) and at the Stanford Linear Accelerator Center (SLAC). Tantalus I, which is most luminous in the ultraviolet part of the spectrum, is operated exclusively for the production of synchrotron radiation. The National Synchrotron Light Source and Aladdin would also be dedicated to the production of synchrotron radiation.



EXTRACTED BEAM of synchrotron radiation is most commonly employed in some form of spectroscopy, in which the interaction of the radiation with matter is measured as a function of wavelength. The synchrotron radiation is naturally well collimated, but it is converted by an elliptical or parabolic mirror into a convergent beam. The mirror must be arranged so that the radiation strikes it at grazing incidence; otherwise a substantial portion of the short-wavelength rays would be absorbed rather than reflected. The beam then enters a monochromator, where a diffraction grating disperses it into a spectrum just as a prism disperses visible light. At ultraviolet wavelengths the monochromator grating is generally a ruled plate of glass; at X-ray wavelengths the orderly rows of atoms in a crystal serve the func-

beam line. At the wavelengths of greatest interest these functions cannot be performed by conventional optical elements such as lenses and prisms, since glass and all other materials absorb ultraviolet and X-ray wavelengths. Instead the beam must be manipulated with reflecting devices, and for the shorter wavelengths even these must be operated at grazing incidence.

The mirrors are of highly polished metal or glass, and in order to provide focusing they are ground as shallow ellipses, hyperbolas or parabolas. For short-wavelength ultraviolet radiation and for X rays even a carefully polished surface would be a poor reflector for a beam striking it near the perpendicular, but reasonable reflectance can be achieved if the beam is almost parallel to the surface. (In a similar way the comparatively rough surface of a blacktop road becomes a specular reflector when viewed at a sufficiently shallow angle.)

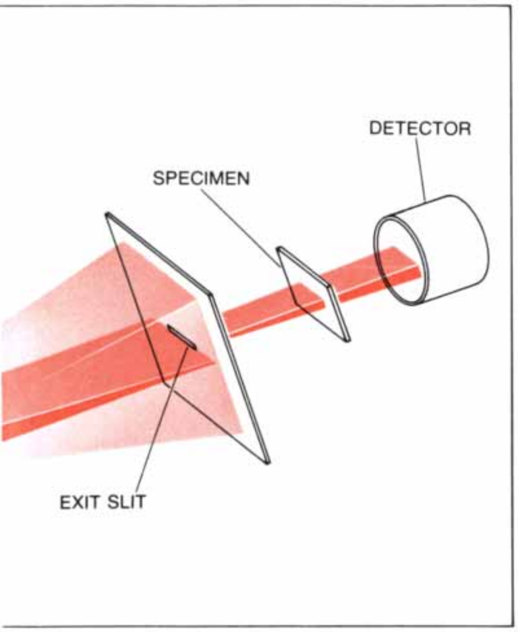
The mirrors focus the beam on the entrance slit of a monochromator. For ultraviolet wavelengths the active element of the monochromator is a diffraction grating: a slab of glass or metal with many closely spaced rulings or grooves (several thousand to the inch). At X-ray wavelengths the regularly spaced rows of atoms in a large single crystal, traditionally quartz but now more commonly silicon or germanium, serve the same function. After striking the diffraction grating or the crystal the narrow beam is dispersed into a spectrum, just as a beam of sunlight is dispersed into a spectrum by a prism. The monochromator is then adjusted so that an exit slit selects the desired wavelength from the dispersed fan of radiation.

It may seem paradoxical that we go to great lengths to find a light source with a continuous spectrum only to throw away all but one wavelength. Why not use a line source in the first place and dispense with the monochromator as well as the synchrotron? The answer is that the output of the monochromator represents the equivalent of a tunable line source, whereas a real line source always has a fixed wavelength. The commonest experimental paradigm involves measuring some property that varies as a function of wavelength. With line sources a series of measurements must be made, each measurement with a separate source of radiation; the result is a sampling of the property at a number of discrete wavelengths. With a continuum source the function can be monitored at all wavelengths as the monochromator is swept through its range.

The earliest and in many respects the simplest measurements made with synchrotron radiation recorded the absorption of radiation by gases. In experiments of this kind the radiation is simply passed through a sample of the gas and the intensity of the transmitted radiation is measured as the monochromator is scanned through its range of wavelengths.

Electromagnetic radiation can be absorbed by an atom in a gas only when the incident photon can in some way alter the state of an electron in the atom. The process is the inverse of photon emission by atoms. Transitions between the various possible orbital states of an electron give rise to discrete absorption lines. In atomic hydrogen, the simplest atomic system, the spectral lines are organized into well-defined series, named for their discoverers: Lyman, Balmer, Paschen, Brackett, Pfund. If we suppose that the atom is initially in the ground state (which is the condition for the Lyman series), then there is a minimum energy below which no transitions are possible. A photon with an energy below that threshold simply is not absorbed. Photons with an energy corresponding to the energy difference between the ground state and the first excited state are very strongly absorbed, but those with a slightly greater energy are not, until the energy of the second excited state is reached. The higher excited states, in which the electron is only weakly bound, are closely spaced, and they converge to a limit: the ionization energy. When the atom is ionized, the electron is no longer confined to a spectrum of discrete states, and so all photons with energies above the ionization limit can be absorbed.

Although the basic rules of atomic spectroscopy were formulated more than 50 years ago, many aspects of the interaction of electromagnetic radiation and atoms are not well understood. For example, in all atoms larger than hydrogen it is possible to excite two electrons



tion of rulings. Finally, the monochromatic beam is directed to the specimen, which might be a solid or a gas. The amount of radiation absorbed, reflected and (in some cases) transmitted by the specimen carries information about the electronic structure of the material.

simultaneously; the resulting state is not simply the sum of the two component excitations, since the two electrons—which in quantum mechanics can be regarded as waves—may interfere with each other. Such simultaneous excitations are produced at a significant rate only with an intense flux of photons, so that these states are more easily studied with synchrotron radiation than with other sources. An excited electron can also interfere with the "hole" it leaves behind in its initial state.

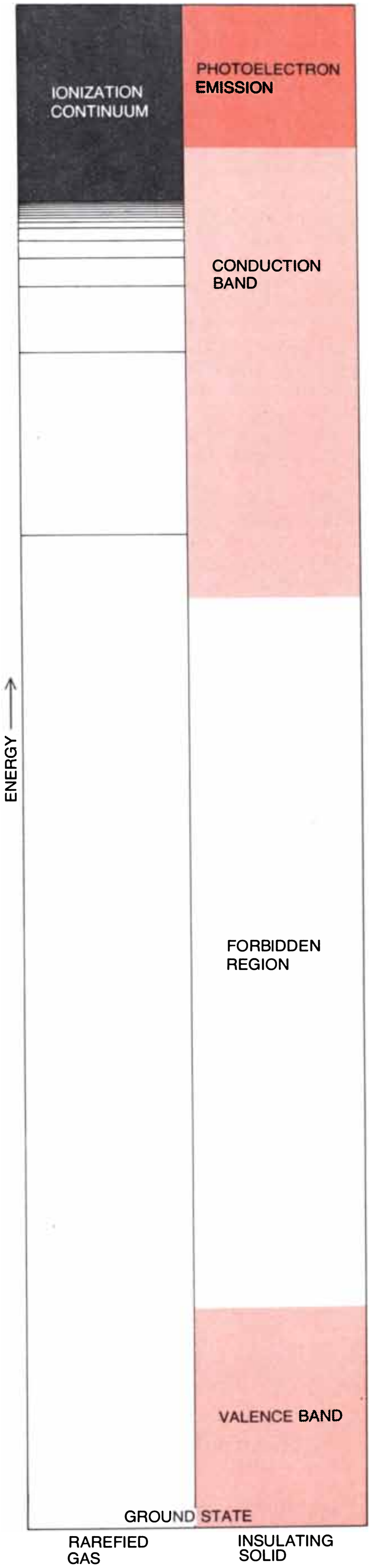
Gases made up of molecules rather than single atoms also have interesting spectra, typically far more complicated than atomic spectra. Molecules have absorption lines—mainly at infrared wavelengths—derived from vibrations and rotations of the molecule. At higher photon energies molecular absorption is continuous, and it leads to the fragmentation of the molecule. The absorption of a high-energy photon may liberate a single electron (ionization), or it may break the molecule into separate atoms or groups of atoms (dissociation). Studies of the absorption spectrum and the fragments created, which are conveniently conducted with synchrotron radiation, provide information on the chemistry of the molecules. They can reveal the energy of the interatomic bonds, the lifetime of excited states and the channels by which those states decay. Rates of chemical reactions and the paths followed by those reactions can also be investigated.

Absorption spectra are not the only properties of gases that can be determined with synchrotron radiation. An atom or a molecule that has absorbed a photon can in some cases dissipate its energy of excitation by emitting another photon of somewhat longer wavelength; this is the phenomenon called fluorescence. By studying the fluorescence spectrum of a gas it is possible to deduce the lifetime and mode of decay of the excited state. The periodic nature of synchrotron radiation suggests an obvious experimental technique: the sample is illuminated by the brief burst of radiation emitted as the electron beam passes, then the fluorescence is detected during the subsequent dark period. If the fluorescence lifetime is much longer than the revolution period, the circulating electron beam can be diverted (with a small magnetic "bump") so that the specimen is illuminated only once in every few revolutions.

Another method of investigating the properties of gases is to analyze the energy and the angular distribution of electrons escaping from an illuminated gas. From such measurements one can determine what the initial state of the emitted electron was. In these experiments the energy of the incident photons is held constant and the energy of the electrons knocked loose is surveyed. By analyzing not only the energy of the emitted electrons but also their spatial distribution with respect to the incident, polarized beam, the symmetry of the initial atomic state can be determined. In this way the quantum-mechanical state of the atom can be completely characterized.

The application of synchrotron radiation that has so far been most eagerly pursued is the spectroscopy of solids. A solid is a great playground for electrons, and the games played there are complex. Observing those games with only a few discrete wavelengths is like watching a football game in only a few isolated strips of the playing field. Little can be learned about the rules of the game from such scanty and discontinuous data.

In a solid the atomic nuclei provide a lattice of point charges among which the electrons are dispersed. Moreover, the



ELECTRONIC STRUCTURES of a gas and of a solid differ mainly in that electrons in the virtually isolated atoms of a gas can occupy only discrete energy levels, whereas those in a solid can have any energy within a comparatively broad band. The gas can absorb only those photons whose energy corresponds to the difference in energy between two allowed states. The solid has a more nearly constant absorption spectrum. Photons with sufficient energy can eject an electron from a gas (ionization) or a solid (photoelectron emission).

electrons are not always confined to the vicinity of the atom to which they nominally belong. The ionic chemical bonds of insulating materials represent an effective transfer of charge from one atom to another; in the covalent bonds of semiconductors the charge is shared by two atoms. In metals the charge distributions of atoms overlap and electrons are free to wander through the bulk solid. Clearly the behavior of such itinerant electrons must differ from that of electrons in stable atomic orbitals. In crystalline solids the high degree of symmetry of the atomic lattice further alters the electronic properties. Since the lattice in a crystal is periodic the same charge distribution appears at equivalent points in all the cells of the crystal. Because of this periodic structure an electronic state in a crystal is no longer completely defined by its energy, as it is in an isolated atom; now the momentum, which defines a direction in space, must also be known. In an atom the energy levels are distinct; in an amorphous aggregate they are broadened into energy bands; in a crystalline solid the bands become well-defined functions of energy and momentum.

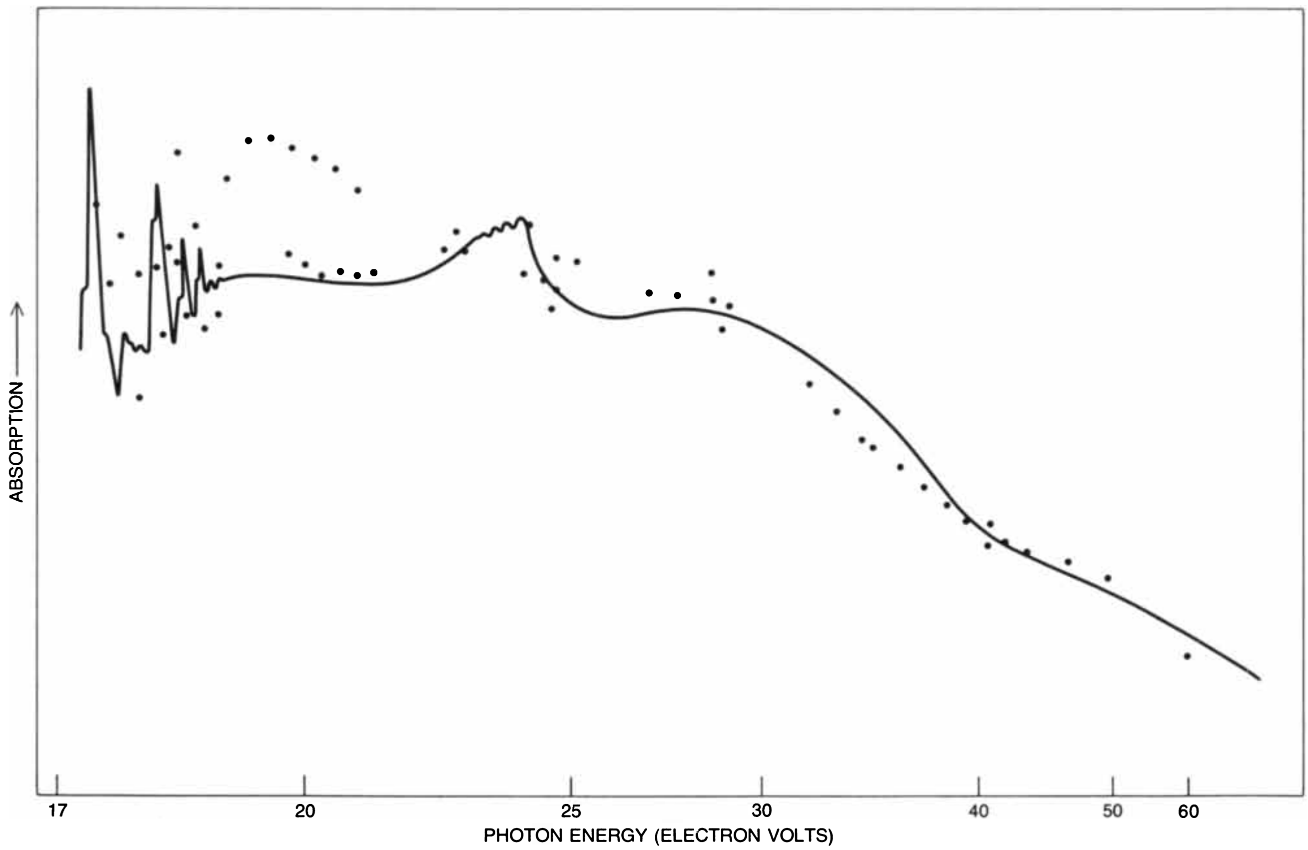
Not all the electrons in a solid form energy bands, only those in the outermost, valence orbital. The inner electrons, being more tightly bound to the nucleus and screened from the environment by the valence electrons, are little affected by the presence of neighboring atoms. With synchrotron radiation both the band structure of the outer electrons and the once inaccessible, higher-energy spectrum of the core electrons can be explored.

There are two main approaches to solid-state spectroscopy. They have in common the illumination of the specimen with a high-intensity beam of photons that is partly absorbed, partly reflected and, if the sample is thin enough or transparent enough, partly transmitted. In one mode the reflected or the transmitted photons are detected. In the other mode electrons emitted by the material following photon absorption are collected and analyzed.

A typical experiment in photon spectroscopy measures reflectivity: the ratio of the incident radiation to the reflected radiation for a range of wavelengths. From the reflectivity data the probability that an electron in the solid will absorb a photon and be excited to some more energetic final state can be determined. The difficulty comes in deciphering the resulting calculated absorption spectrum, since neither the initial state nor the final state is known, only the energy difference between them.

Additional information on the electronic structure of solids comes from studies of the electrons ejected from the surface of an illuminated material. For most substances the threshold for photoelectron emission (analogous to the ionization energy in atoms) is in the ultraviolet, and synchrotron radiation greatly facilitates the recording of a spectrum. In one type of experiment, in which a tunable source is indispensable, the energies of the incident photons and of the detected electrons are scanned simultaneously. The resulting spectrum indicates the distribution of final states.

An electron knocked loose from a solid can convey information about its initial state only if it escapes from the solid without being deflected by other atoms. For this reason photoelectron spectroscopy is particularly useful in studies of surfaces: it probes the outermost atomic layers. Surfaces are even more complicated systems than bulk solids, since the periodicity of the lattice is disrupted. Surfaces contaminated with adsorbed atoms and molecules and clusters of molecules are still more difficult to describe. Measurements of photoelectron



ABSORPTION SPECTRUM of molecular nitrogen (N_2) was measured with synchrotron radiation. The sharp peaks and troughs at the far left represent transitions between electronic energy levels within individual nitrogen atoms; the continuous absorption at higher energies results from ionization. The series of small bumps in the curve at about 23 electron volts is caused by rotational and vibrational excitations of the diatomic molecules. The dots are individual absorption measurements made with line-emission sources of radiation. The detailed structure of the absorption spectrum is apparent only in continuous measurement made with synchrotron radiation.

emission have revealed profound changes in optical properties as a clean surface is progressively covered with an atomic monolayer.

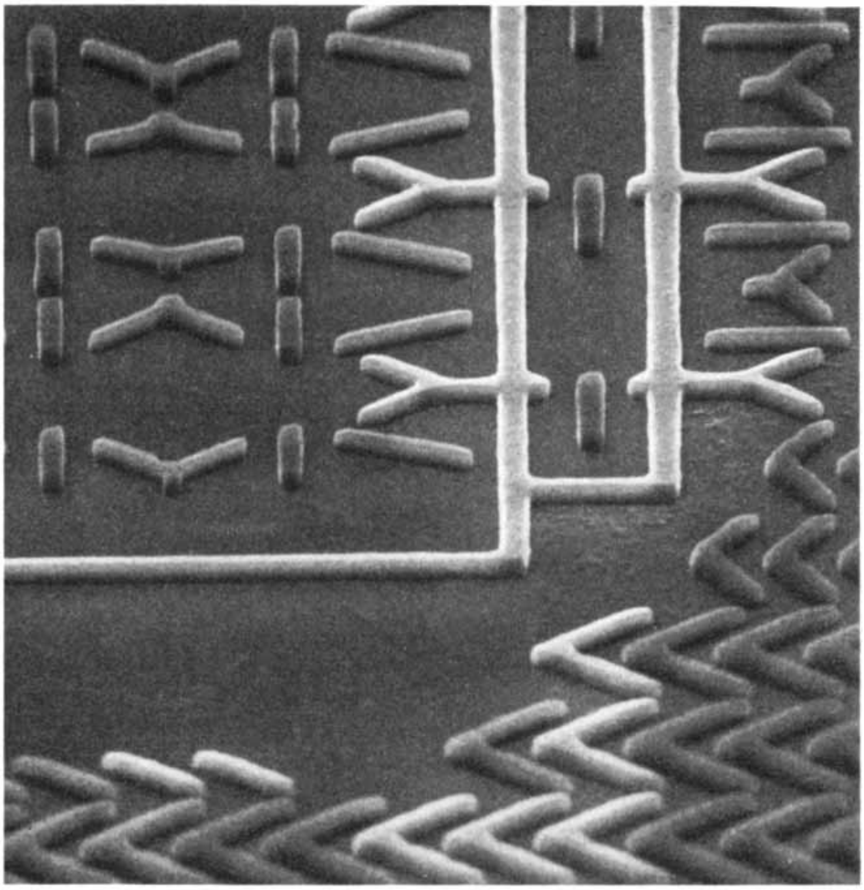
Absorption spectra for solids can be measured in the traditional way—by determining the ratio of transmitted to incident radiation—just as they are for gases. The near-opacity of the solids complicates the measurements and requires that the specimens be thin—a few hundred angstroms in thickness.

At ultraviolet and X-ray wavelengths the absorption spectra of solids have characteristic "edges," where a threshold for the excitation of an inner-shell electron is crossed. Some of these edges are very sharp, that is, the absorption changes drastically for a small change in wavelength. When such an edge is observed with a high-resolution instrument, it is possible to detect the small changes in the state of the core electrons that result from changes in the configuration of the surrounding atoms. These effects can be seen only with synchrotron radiation, since no other source of illumination provides a sufficiently intense continuum.

So far the capabilities of synchrotron radiation have been exploited mainly at ultraviolet and low-energy X-ray wavelengths. The storage rings at SPEAR and DESY give access to higher-energy X rays, and recently several investigators have devised techniques for employing them. Among these techniques is the investigation of X-ray-absorption fine structure, which recovers from the absorption spectrum information about the scattering of photoelectrons by atoms in the lattice surrounding the electron's site of emission [see "The Analysis of Materials by X-Ray Absorption," by Edward A. Stern; SCIENTIFIC AMERICAN, April, 1976].

Further afield, synchrotron radiation promises to transform the technology employed in making integrated circuits. These microelectronic devices are made by etching successive layers of circuitry into a wafer of silicon or another semiconductor material. The pattern of the circuitry is defined by illuminating a photoresist through a "mask," or stencil; the exposed portions of the resist can then be washed away.

Present barriers to further reductions in the size of integrated circuits arise not from the requirements of the circuit elements themselves nor from the limitations of mask-making. The minimum size is set by diffraction effects that blur the pattern exposed through the mask. At visible wavelengths the resolution is inherently limited to somewhat more than 10,000 angstroms. By exposing the resist with synchrotron radiation at a wavelength of 20 angstroms, the resolution of the pattern can approach 100 angstroms, an improvement by a factor of 100.



X-RAY LITHOGRAPHY employing synchrotron radiation brings high resolution to the fabrication of microelectronic devices. The pattern of the circuitry for such a device is laid down by exposing a light-sensitive resist through a stencil. At visible wavelengths diffraction would blur any circuit element smaller than about 10,000 angstroms. In the device depicted here the thinnest lines are about 100 angstroms wide. The pattern shown is part of a memory device that manipulates regions of reversed magnetic polarity. The exposure was made at DESY by Eberhard A. Spiller and his colleagues of the International Business Machines Corporation.

The same photoresist can also be employed in a novel system of X-ray micrography. A specimen, perhaps of a biological structure, is placed on a uniform field of resist and exposed to short-wavelength synchrotron radiation. The specimen is then removed and the resist is etched. The relief pattern remaining is a three-dimensional graph of the X-ray absorption of the specimen.

The most reliable indication of the scientific community's interest in synchrotron radiation is that the demand for the facilities has outrun the supply. Plans have been formulated for improving existing machines and for building at least two new storage rings that would be dedicated entirely to generating synchrotron radiation.

The electron-positron storage ring at SPEAR now has two synchrotron-radiation ports, split so as to serve eight experimental stations. They are intended primarily for work at higher-energy X-ray wavelengths. It is now planned to add seven beam lines serving 14 additional experimental positions. Moreover, a new electron-positron storage ring, called PEP, is now under construction near the SPEAR ring. When PEP begins operating in 1980, a major share of the operating time at SPEAR is expected to be set aside for synchrotron-radiation research.

At the Synchrotron Radiation Center of the University of Wisconsin, where Tantalus I now operates, the building of a new storage ring to be called Aladdin has been proposed. The machine would provide both higher energy (750 MeV) and higher intensity, and it would have from 30 to 40 radiation ports.

Finally, an entirely new synchrotron-radiation facility, with two storage rings, has been proposed for the Brookhaven National Laboratory. A comparatively small ring, operating at 700 MeV, would generate synchrotron radiation at wavelengths ranging from the ultraviolet through low-energy X rays. High-energy X rays would be produced in a larger storage ring with a maximum energy of 2.5 billion electron volts. The Brookhaven installation, to be called the National Synchrotron Light Source, would have a total of almost 50 beam lines.

Microbial Life in the Deep Sea

How is the metabolism of microbes influenced by the high pressures and low temperatures of the deep-sea environment? The question is investigated by experiments on the sea floor and in the laboratory

by Holger W. Jannasch and Carl O. Wirsen

Ever since the pioneering oceanographic expedition of the *Challenger* in 1872 it has been known that life can be found down to the greatest depths of the ocean. This means that the biosphere, the thin layer at the earth's surface where life exists, is 99 percent seawater. The total plant production and recycling of organic matter on land exceeds that in the sea, but the fact remains that every day large quantities of organic materials produced in surface waters sink to the ocean floor. The populations of animals and microorganisms in the deep water depend entirely on these materials for their existence. The microorganisms, particularly bacteria, are ubiquitous in the deep sea. It seems likely that their important role in the conversion of plant and animal remains back into inorganic materials is similar to that on land. The fertility and biological productivity of the oceans depend on these processes, and so does man's involuntary or voluntary utilization of the sea as a dumping ground for organic wastes.

The environment of the deep sea is characterized by extremes. Virtually no light penetrates the ocean below 200 meters. Thus no photosynthetic organisms can grow at greater depths. Except for a few specific areas, the temperature of all the oceans falls to within a few degrees above freezing within the first several hundred meters. With each 10-meter increase in depth the pressure exerted by the surrounding water increases by about one atmosphere (14.7 pounds per square inch).

To place the bacteria in perspective within the world of living cells it should be kept in mind that they have the basically simple organization of prokaryotes. In the eukaryotic cells of higher organisms, which seem to have evolved only some 700 million years ago, the genetic material that will be passed on to the next generation is segregated in the cell nucleus. In prokaryotic cells, which are thought to be more ancient and primitive, there is no membrane-enclosed cell nucleus and the genetic material is distributed throughout the cell. All bacteria and certain primitive plants (the blue-green algae, also known as cyanobacteria) are prokaryotes. These organisms are among the oldest-known forms of life on the earth.

Bacteria are characteristically single-celled organisms, which generally reproduce by cell division. Some have dormant stages that are capable of "resting" in a state of suspended animation for long periods. Whether bacteria are active or resting they are able to survive great extremes of pressure and temperature. There are a great many physiological types of bacteria, each making its living by different metabolic pathways in the oxidation and reduction of organic and inorganic materials.

Bacterial life in the deep sea is not easy to study. When bottom sediments or deep-water samples are brought to the surface and small quantities of suitable nutrients are provided, profuse bacterial growth usually occurs. In the laboratory, of course, these bacteria are normally cultured free of the constraints of low temperature and high pressure that were present in their original environment. The first laboratory experiments designed to subject such deep-sea organisms to the same pressures that are found at various ocean depths were conducted in the late 1940's by Frank H. H. Johnson of Princeton University and Claude E. ZoBell of the Scripps Institution of Oceanography. Culturing their bacteria inside pressure vessels, they found that increased pressures adversely affected both the metabolism of the bacteria and the activity of isolated bacterial enzymes. They also found, however, that the bacteria were not all affected equally: the degree of barotolerance, or pressure tolerance, varied greatly from one bacterial culture to another.

These experiments and similar ones had an obvious drawback: in being brought up from the deep sea the bacteria had to be decompressed before their normal environmental pressure could be restored. Today, with the development of new approaches to high-pressure technology and deep-sea reconnaissance, this problem can be faced squarely. Heretofore when deep-sea bacteria arrived in the laboratory, the samples had been decompressed by several hundred atmospheres for various periods of time. This kind of decompression, normally fatal to any higher organism, did not seem to affect many of the bacteria adversely. At least some of them flourished once they were provided with nutrients in the laboratory.

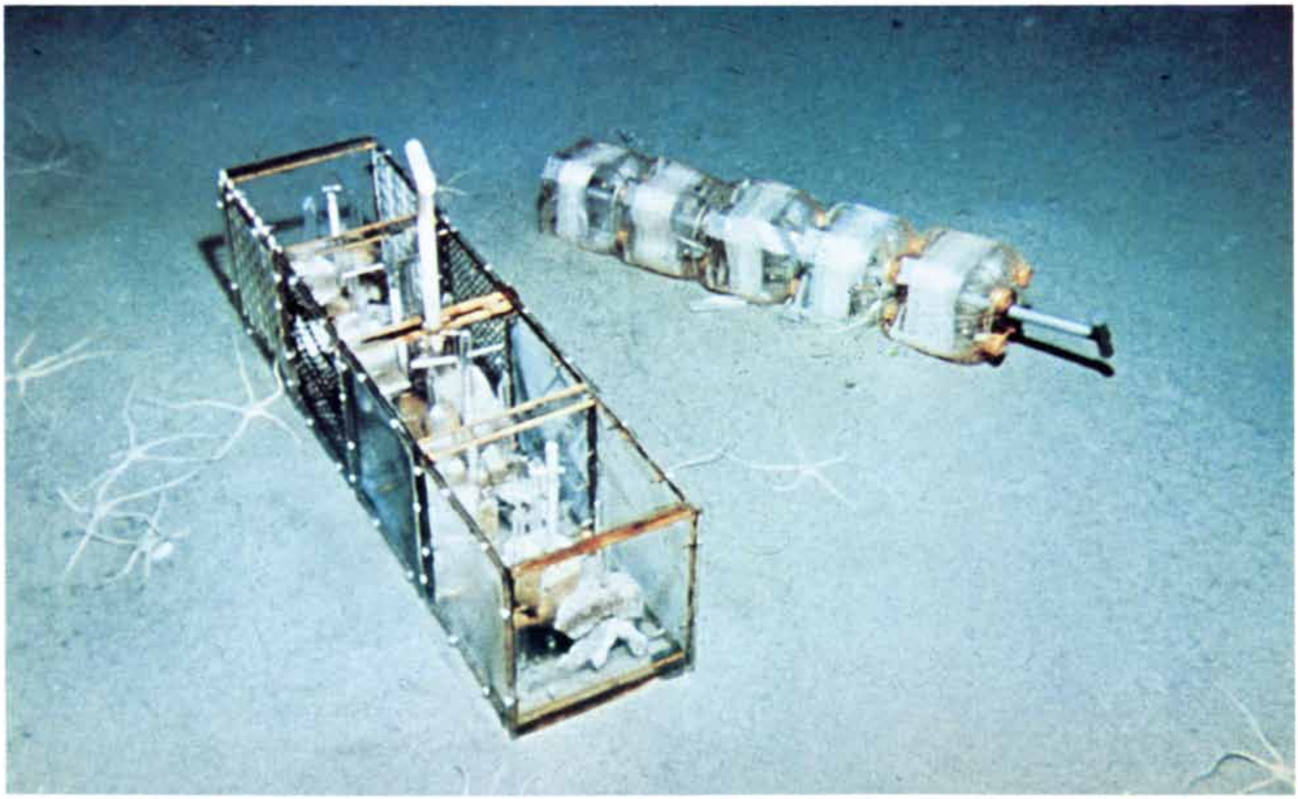
The fact that these mixed bacterial populations had been decompressed nonetheless raised a number of questions. Were the bacteria that thrived in the laboratory equally active in the deep sea? Were there some kinds of bacteria that had failed to survive decompression? Such bacteria might be specifically adapted to life in the deep sea. Bacterial adaptations of this type are familiar with respect to extremes of temperature.

Bacteria that can grow well at low temperatures are called psychrophilic, or cold-loving. They do not, however, grow faster at low temperatures than other nonpsychrophilic bacteria do at higher temperatures. They are simply able to tolerate low temperatures at which other bacteria do not grow. They may not survive room temperature, and when they are being isolated and cultured from cold seawater, the temperature must be kept below 18 degrees Celsius at all times.

Barotolerant bacteria might behave similarly, that is, decompression might prove fatal to them. This might apply particularly to those bacteria that have been described as barophilic, or pressure-loving. These organisms would grow faster at high pressure than at normal atmospheric pressure. To search for evidence of such an adaptation seemed a worthy endeavor.

To mount the search at first appeared to require such a large investment in complex apparatus as to be unattainable in the foreseeable future. Such at least was our conclusion until an incident in 1968 suggested a fresh approach. In that

RESEARCH SUBMERSIBLE *Alvin* **placed and retrieved most of the experiments described in this article. Seen here at the start of a dive, the vessel can descend as far as 3,700 meters. The experimental equipment is carried in the basket that is attached to the vessel's bow.**



TWO DEGRADATION EXPERIMENTS are shown in progress at a depth of 1,830 meters. The four compartments of the Plexiglas box (*front*) are baited with organic materials. Screens with mesh of different sizes restrict deep-sea animals' access to the bait. The cylindrical rack (*rear*) contains 20 bottles filled with nutrient. When the bottles are on the bottom, they fill with seawater containing microbes.

year the *Alvin,* a deep-sea research submersible that was entering its third year with the Woods Hole Oceanographic Institution, was being readied for a descent about 100 miles south of Nantucket Island when it accidentally sank in 1,540 meters of water. The pilot and two scientists escaped, but they had left their box lunch aboard for an unintended experiment.

Outlined in a grant application, the experiment might have been titled "A Study of the Biodegradation of Selected Organic Materials in the Deep-Sea Environment." The applicant could have described the apparatus as a plastic container designed to exclude all organisms but microscopic ones and could have listed the test samples as including carbohydrates, proteins in both solid and liquid form, fats and a sample of intact plant material. In translation this means that the box lunch consisted of bouillon, a bologna sandwich with mayonnaise and a dessert of apples. When the *Alvin* was brought to the surface 11 months after sinking, the box lunch was in a remarkably good state of preservation. It was refrigerated at once and held at the equivalent of deep-sea temperature: three degrees C. Within a few weeks the food had spoiled.

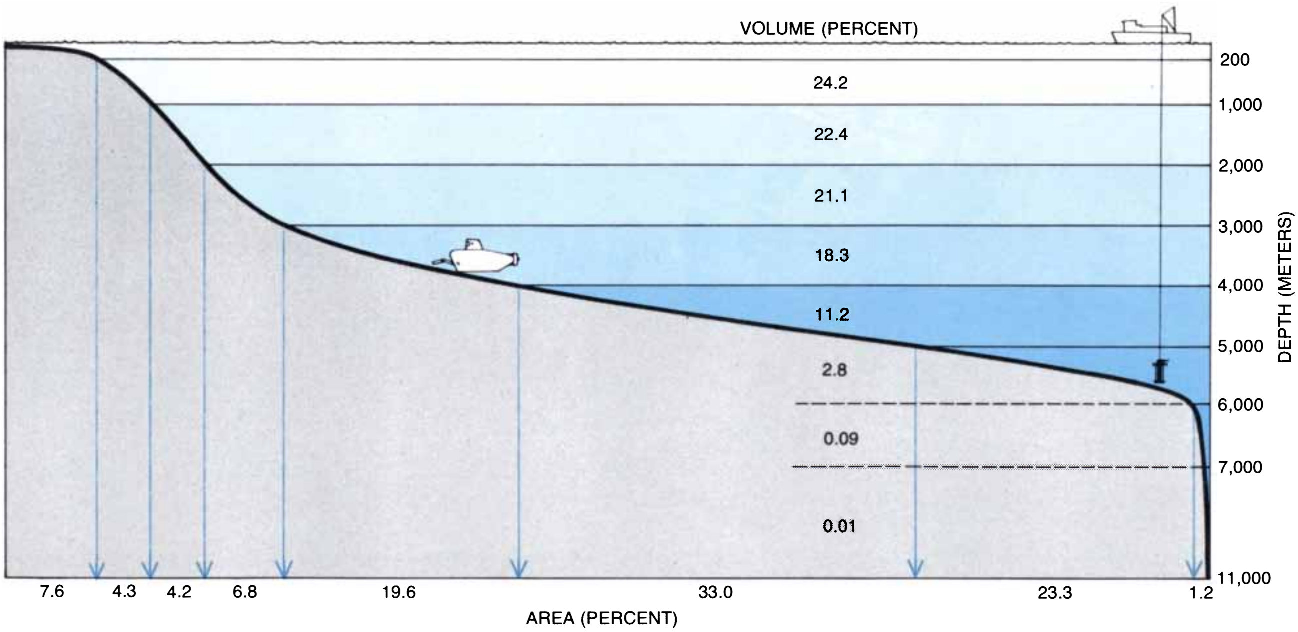
The unintended experiment led to observations that were intriguing but not yet conclusive. More important, it gave rise to a fresh thought: with little difficulty we could conduct similar experiments under reproducible and rigorously defined conditions. It would only be necessary to attach packages of samples to the mooring lines used in various ongoing experiments in physical oceanography. We could allow the contents of the packages to incubate for periods ranging from two to six months at depths as great as 5,300 meters. The bacterial growth and metabolic activity supported by the various organic nutrients in each package would take place not in the laboratory but under the normal deep-sea conditions of low temperature and high pressure. When the mooring lines were retrieved, we could determine the growth and extent of metabolic activities of the incubated bacteria by measuring the quantity of nutrients consumed or converted during immersion.

We pursued this experimental strategy, submerging packages that contained various pure cultures or natural populations of bacteria in association with solid or liquid nutrients of different kinds. For each submerged package we prepared a duplicate control package that was incubated in the laboratory at temperatures that matched the temperature of the water surrounding the submerged package: from two to 3.5 degrees C. The control packages were incubated at normal atmospheric pressure.

One of the nutrients we used was fresh fish meat, a complex and highly degradable material. The meat decomposed much more slowly at a depth of 5,300 meters than the control samples did in the laboratory. Other materials in the packages included agar (the product of certain marine algae), chitin (the principal component of the external skeleton of many marine invertebrates), gelatin (a proteinaceous nutrient) and starch (a carbohydrate). By using radioactively labeled nutrients we were also able to make quantitative measurements. For example, labeling with radioactive carbon enabled us to accurately determine the bacterial cells' incorporation of carbon from carbohydrates, from amino acids and from fatty acids and also to measure the amount of carbon dioxide produced by respiration. The rate of metabolism of the bacteria incubated in deep water was in each instance far lower than the rate of the controls incubated in the laboratory; in many instances it was 100 times lower.

The bacteria used in our initial experiments were collected from surface waters. We expected to obtain data of even greater interest if our experiments involved only bacteria that lived under deep-sea conditions and were possibly adapted to them. To that end we designed a somewhat more elaborate apparatus. We used bottles that contained sterile nutrients and were sealed with a rubber stopper. Each stopper was perforated with a slit, which remained tightly closed after the bottle had filled on the deep-sea floor.

The bottles were placed in a pressure-proof aluminum housing (a cylinder with a removable lid, fitted with a valve that could be opened from the outside). One or more of the housings were then carried by the *Alvin* to two permanent deep-sea bottom stations, located in the Atlantic off Cape Cod at a depth respectively of 1,830 and 3,640 meters. Once the *Alvin* was on station at the bottom the pilot used the submersible's mechanical arm to open the valve on the housing, letting it fill either with seawater or with a slurry of water and bottom sediment. The pressure at these depths forced the water or the slurry through



DEEP SEA, water 1,000 meters or more deep, underlies 88 percent of the surface area of the world ocean and includes 75 percent of the total volume. The highly productive surface layer, 200 to 300 meters deep, and abyssal water below 6,000 meters add little to total volume.

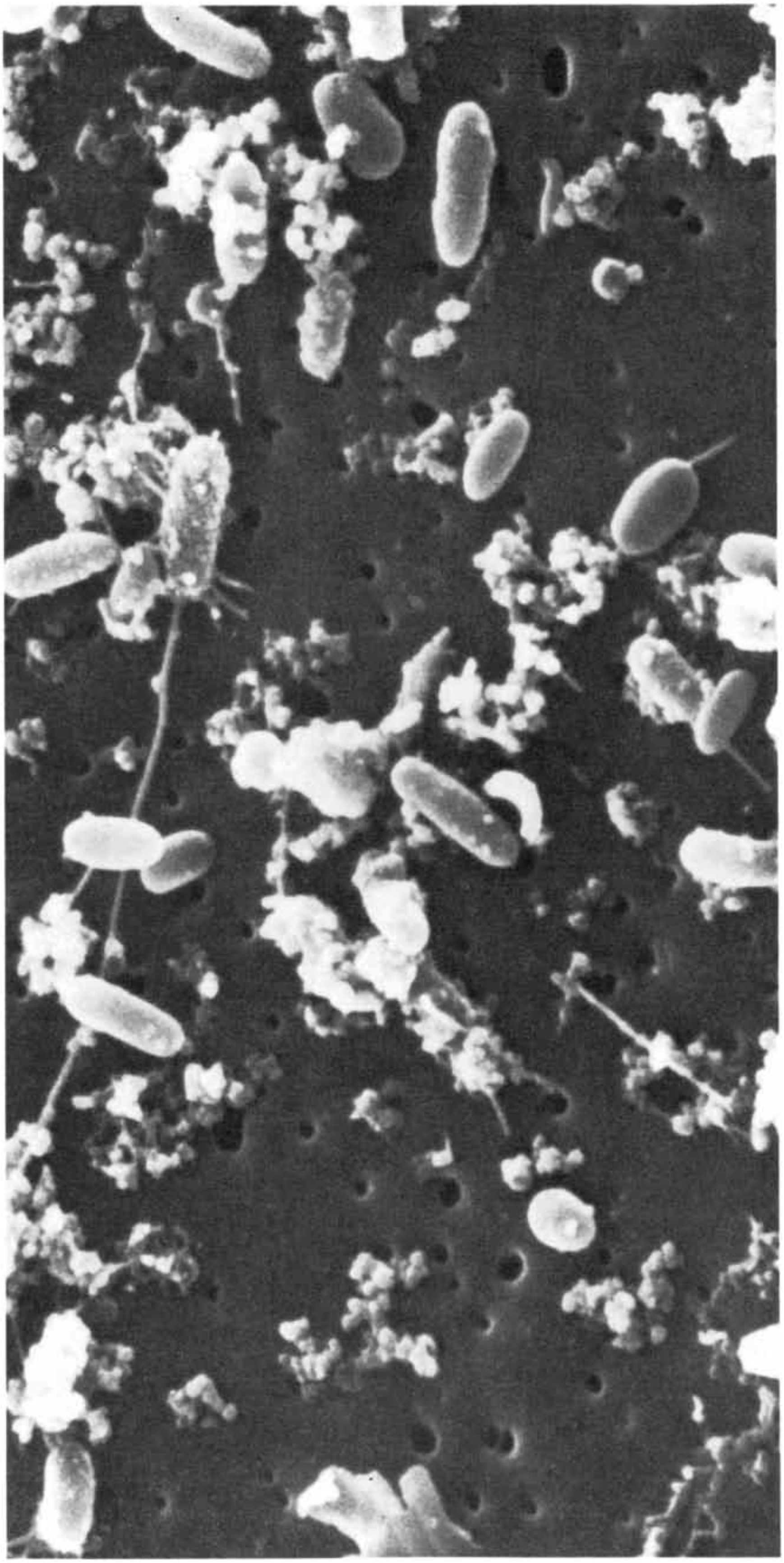
the slits in the rubber stoppers, thereby inoculating the nutrients in the bottles. The equalization of pressure inside and outside the housing after it was filled made it possible for the *Alvin*'s mechanical arm to remove the housing lid, lift out a rack holding the bottles and deposit it on the ocean floor. On the next visit to the deep-sea station the bottles were retrieved for analysis on board ship.

The results of these in situ experiments, which made it possible to conduct growth studies in the absence of decompression, were surprising. After incubation periods ranging from two to 15 months the deep-sea bacteria were found to have utilized the supplied nutrients at about the same low rate that bacteria from the surface had. No barophilic bacteria appeared to have been active. As for barotolerant bacteria, as distinct from barophilic ones, there seemed to be no more of them among populations of deep-sea origin than there were among the bacteria present in the surface waters.

Reviewing our experimental design, we could still see two disadvantages that might be overcome. First, our system gave us only a single end-point measurement of the organisms' metabolic activity rather than day-by-day measurements; thus it could not tell us whether the rate was constant throughout the period of incubation. Second, the abrupt equalization of external and internal pressures when the valves of the aluminum housings were opened exposed some of the entering bacteria to pressure shock and high shear forces. It was clear that we should eliminate both disadvantages in future experiments. We saw only one way to do so: to develop a vessel that would gently collect deep-sea bacterial populations and keep them under both in situ pressure and in situ temperature on their return to the laboratory, where respiration and nutrient uptake could be measured day by day.

The design of such a vessel appeared difficult at first, but Clifford L. Winget and Kenneth W. Doherty, Woods Hole engineers experienced in the development of deep-sea apparatus, came to our aid. The first deep-sea sampler was completed and successfully used in 1973. We now have two samplers in operation; one can retain pressures of up to 200 atmospheres (a maximum sampling depth of 2,000 meters) and the other pressures of up to 600 atmospheres (a maximum sampling depth of 6,000 meters).

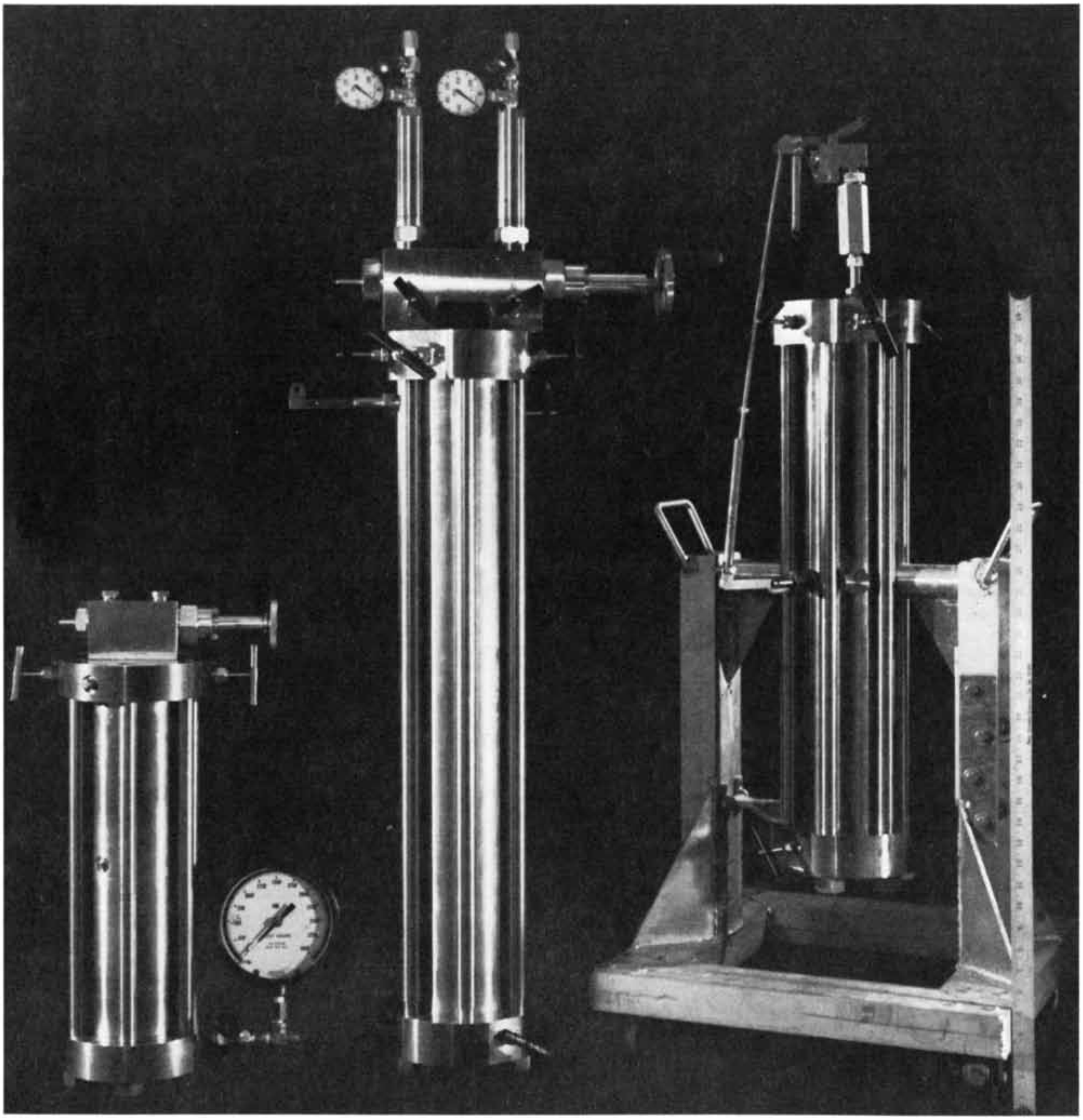
To collect the bacteria we lower the sampler at the end of a cable; when it reaches the desired depth, a "messenger" weight is released and travels down the cable. The weight strikes a lever that opens the filling valve. The cylindrical interior of the sampler is divided in two by a plate perforated by a fine orifice



DEEP-SEA BACTERIA, collected at a depth of 4,400 meters with a sampler having a fine filter membrane, appear as elongated ovoids and thin threads in this scanning electron micrograph. The irregularly spaced holes are the pores of the filter. Granules that are interspersed among the bacteria are artifacts of fixing process. Bacteria are magnified some 20,000 times.

that acts as a flow-snubbing device. Above and below the dividing plate are two free-floating pistons. Before the filling valve is opened the upper piston rests against the top of the cylinder, supported by a column of sterile fresh water; the lower piston rests against the dividing plate, supported by a cushion of pressurized nitrogen gas.

When the filling valve is opened, the pressure differential and shear forces on the entering seawater are at once eliminated by the incompressibility of the fresh water passing through the flow-snubbing orifice. The rate of descent of the piston is predetermined by the setting of the flow snubber in the dividing plate, which admits the water into the lower half of the cylinder. The entering water pushes the lower piston down, compressing the cushion of nitrogen gas. After about 20 minutes a liter of deep-sea water has entered the Teflon-lined top of the sampler cylinder and the pressure of the gas cushion in the lower section of the sampler has equalized with the outside pressure. A check valve then closes and the sampler is hauled aboard and moved into a cold room where the deep-sea temperature is main-



DEEP-SEA MICROBIOLOGICAL SAMPLERS include two steel vessels (*left and right*) capable of retaining the pressure of samples of seawater taken respectively at depths of up to 2,000 and 6,000 meters. The pressures at those depths are approximately 200 and 600 atmospheres. The two vessels also serve as incubators when nutrients are added by means of a transfer unit (*top of vessel at left*); the seawater sample enters the vessel through a triggering intake mechanism (*top of vessel at right*). A more elaborate sampler (*center*) has a filter that concentrates the water's microbial content. The transfer unit on top of the sampler is used to withdraw part or all of the concentrated sample while maintaining deep-sea pressures. Mechanical details are shown in the illustrations appearing on the next two pages.

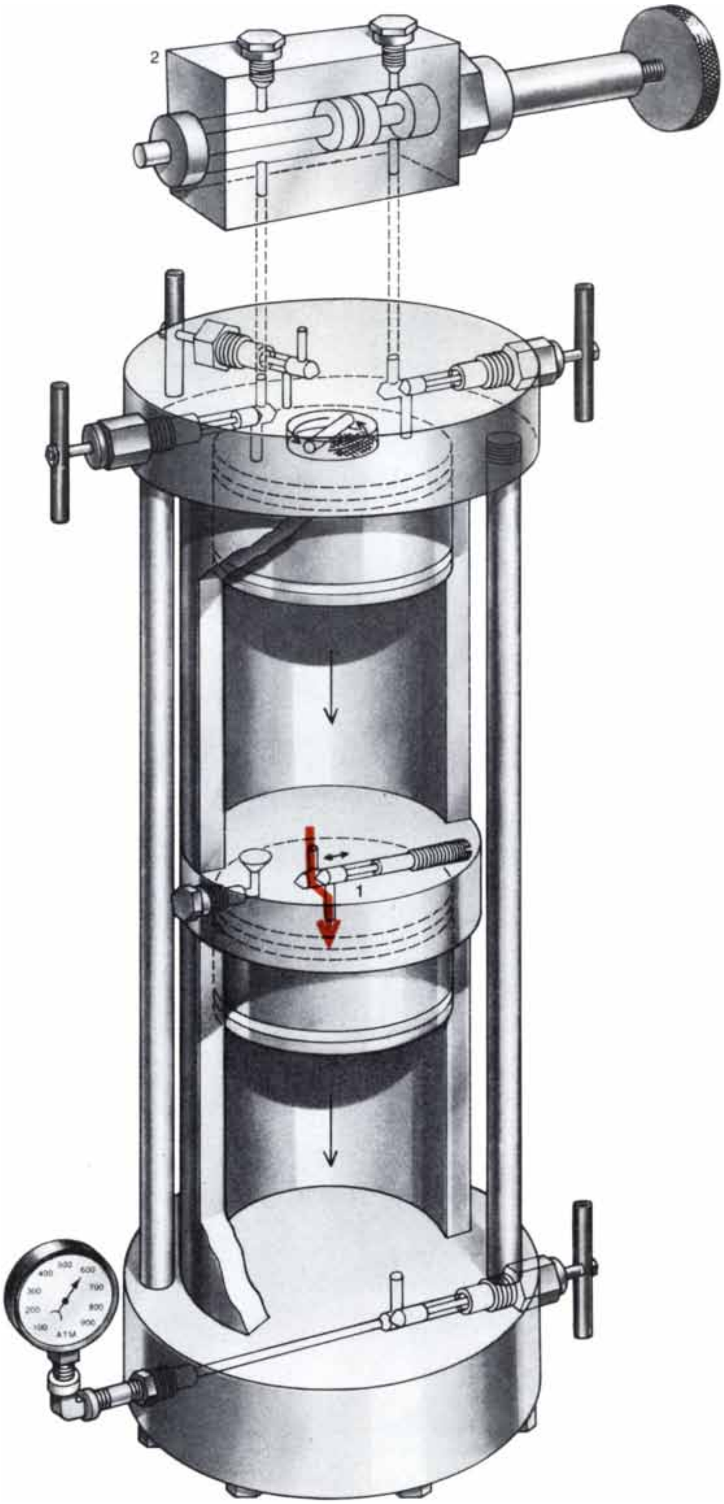
tained. The function of the gas cushion is to prevent a loss of pressure due to the expansion of the vessel, the compression of O-rings and the attachment of pressure gauges.

At this point time-course experiments on nutrient uptake and respiration under pressure are begun. The sampler is now used as an incubation chamber equipped with a magnetic stirrer. Subsamples of as much as 13 milliliters containing radioactively labeled nutrients are added and withdrawn simultaneously by a simple transfer unit. Prior to being attached to the incubation chamber the transfer unit is entirely filled with liquid medium: a nutrient medium or sterile seawater. When the connecting valves are opened, the slight compressibility of this medium is easily compensated for by the nitrogen-gas cushion in the lower section of the incubation chamber. The single piston in the transfer unit is then moved by a hand-operated crank from one side to the other, so that the liquid medium is introduced while an equal volume is withdrawn. After the connecting valves have been closed the subsample in the transfer unit is decompressed and used for analysis. This procedure is repeated hourly, daily or at longer intervals. A control population is studied at normal pressure.

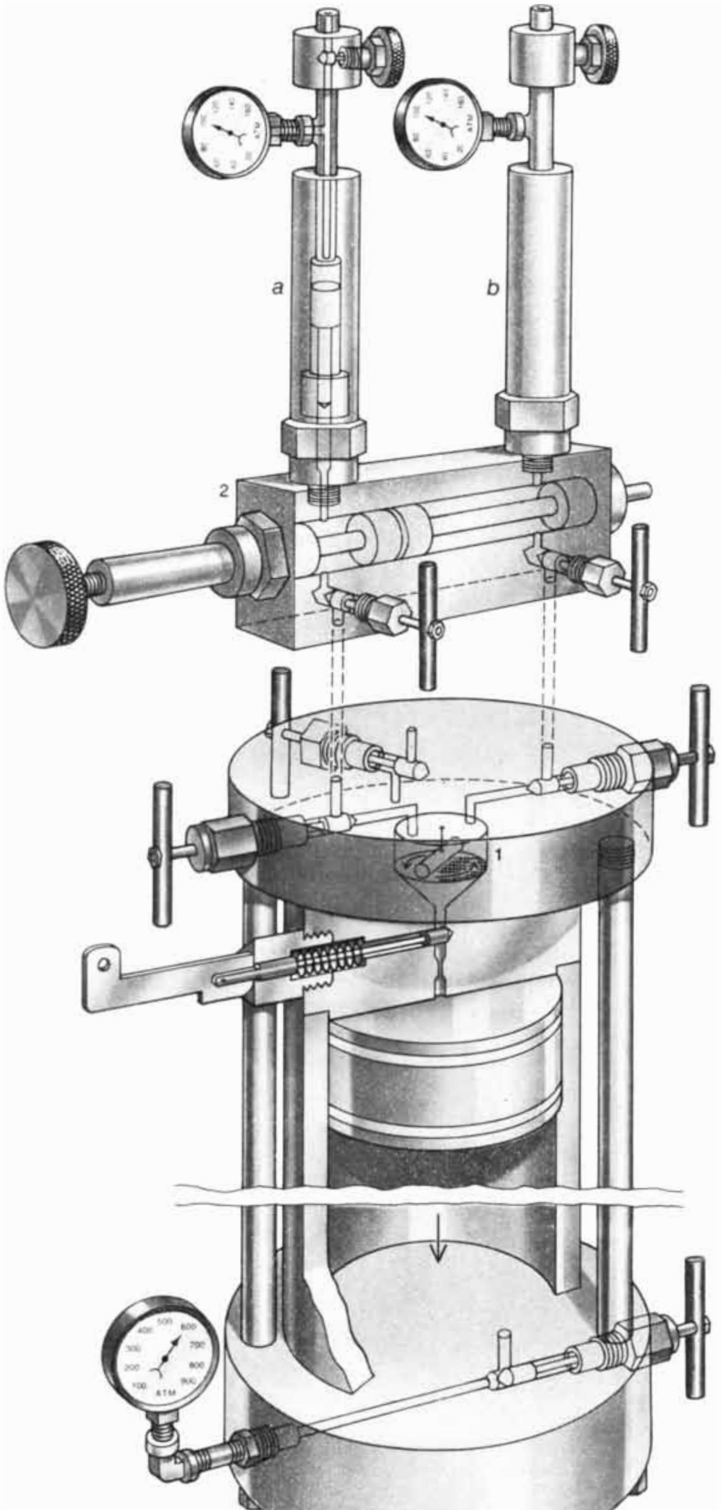
With two such samplers we are able to obtain two samples of deep-sea bacteria during a cruise, but only two. To increase our sampling efficiency we developed a system for the in situ concentration of samples by filtration and for the subsequent storage of the concentrated samples in specially designed transfer units. In this new filter sampler three liters of water passes through a fine filter membrane, concentrating the contained microorganisms and particles 200 times to a volume of 15 milliliters.

Because of technical difficulties in deep-sea studies single observations cannot easily be verified or substantiated by repeated observations. As a result they often receive more attention than their actual significance merits. To be of value the data must be reproducible and backed up by meaningful controls. The advantage of the filter-sampler system thus lies in its acceleration of the data-gathering process.

The results of our laboratory work with deep-sea samples over the past two years have in general supported the findings of our earlier in situ incubation experiments. That is to say, the high-pressure and low-temperature environment of the deep sea has the same effect on undecompressed deep-sea bacterial populations as it does on bacteria collected at the surface. When the deep-sea populations were relieved of the high-pressure constraint of their normal environment, their metabolic activity generally increased. In other words, although



MICROBIOLOGICAL SAMPLER is lowered by winch to collect samples of seawater at depths of up to 6,000 meters and pressures of up to 600 atmospheres. A central plate divides the sampler into two cylinders; an orifice in the plate (*1*) acts as a flow snubber. Before the intake of a sample the upper of two free-floating pistons (*black*) is at the top of the upper cylinder, supported by a column of fresh water; the lower piston is also at the top of its cylinder, supported by pressurized nitrogen gas. When the intake (not shown) is opened, admitting a sample of seawater, the upper piston slowly descends as the fresh water is forced into the lower cylinder (*color*). The lower piston descends reciprocally, compressing the nitrogen gas until its pressure is equal to the outside pressure. A check valve then closes, and the sampler is hauled back to the surface. The sampler is sufficiently insulated to maintain the temperature of the sample at a deep-sea value pending refrigeration of sample on board ship. Transfer unit (*2*) allows withdrawal of portions of the sample or introduction of nutrients without loss of pressure.



FILTER SAMPLER, also designed to hold samples at pressures of up to 600 atmospheres, concentrates 200-fold microorganisms and particulate matter present in a three-liter sample of seawater by passing the incoming sample through a fine membrane filter (*1*). A single-piston system with a flow-snubbing device resembling that in the nonfiltering sampler similarly prevents pressure shock and eliminates high shear forces during the acquisition of the sample on opening the intake (not shown). A special transfer unit (*2*) is equipped with small gas cushions (*a, b*) that prevent loss of pressure during prolonged storage. Some or all of the concentrated sample is withdrawn into one or more pressurized transfer units and is stored at deep-sea temperature on board ship. On return to port the samples are transferred to pressurized incubation chambers. The system allows sterilization and reuse of filter sampler many times on a cruise, since as many samples may be taken as there are pressurized transfer units to retain them.

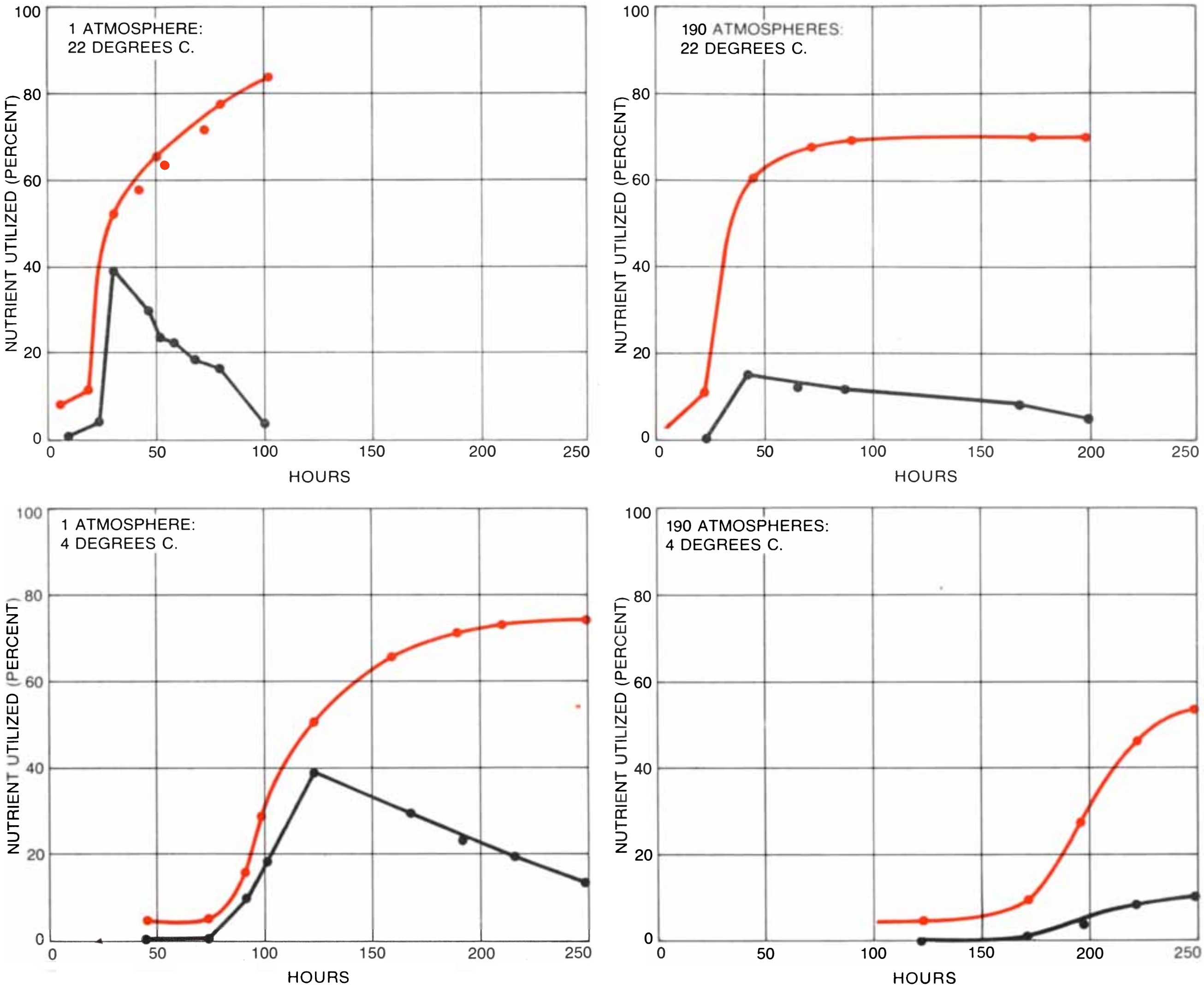
the degree of barotolerance among the bacteria varies, no genuinely barophilic responses have been recorded in these studies.

Does this mean that no such bacteria exist? Not necessarily, for two reasons. First, it is likely that a barophilic response would depend on the kind of nutrient supplied. For example, one of our labeled nutrients is acetate, and our most recent data show metabolic activities with this nutrient that are quite different from those with two other nutrients: glutamate and a mixture of amino acids. This observation needs to be followed up. Second, all the samples tested so far have been mixed natural populations of bacteria. When one considers how many of these bacteria might be surface forms that have reached the deep sea by sedimentation, it is conceivable that in spite of their low metabolic activity their large numbers conceal the activities of a smaller pressure-adapted population in residence. The final word on whether or not truly barophilic bacteria exist can only be said after we are able to study pure cultures of isolated, undecompressed deep-sea strains.

The fishes and invertebrates (such as crustaceans and starfish) that inhabit the deep sea feed on the fragmented carcasses of other marine animals. Some of the more resistant fragments, such as chitin, can only be digested, however, with the aid of bacterial enzymes. This led us to speculate that the gut of deep-sea animals may constitute an ecological niche peculiarly suited to barotolerant or barophilic bacteria. J. A. Allen and Howard L. Sanders of Woods Hole found that the gut of mollusks from deep-sea habitats is considerably larger than that of their shallow-water counterparts. This observation lent weight to our notion of the gut as a special bacterial niche. Therefore over the years we have tested the microorganisms from the gut contents of various deep-sea animals, both mixed populations of bacteria and pure cultures from single isolated bacteria, to see if any might be barophilic. The responses of these bacteria, however, amounted only to various degrees of barotolerance. They were similar to the responses of bacteria obtained in samples of deep-sea water and bottom sediments.

This result is not necessarily surprising, because much of the microscopic life in deep-sea sediments may well stem from the gut bacteria in the feces of browsing deep-sea animals. These studies do not conclusively rule out the existence of barophilic bacteria. The final answer must await studies with pure cultures of undecompressed bacteria.

That animals as well as bacteria contribute substantially to the decomposition of organic debris in the deep sea was a fact well known to us but one we



SEAWATER MICROBES, collected from natural populations found in surface waters, were tested for carbon uptake (*black*) and respiration (*color*) under varying conditions of pressure and temperature. Both high pressure and low temperature affected activity. Pressure affected carbon uptake more than it did respiration. Temperature induced a pronounced lag in metabolism and a lower metabolic rate.

did not specifically study. The incubation devices used in our experiments excluded any organism larger than 100 micrometers in diameter. We therefore thought it would be useful to compare the contribution to the total decomposition made by both bacteria and larger decomposers. One apparatus for this purpose consisted of an array of vertical plastic tubes. Each tube was divided into four compartments, each of which was accessible from the outside by way of a circular hole. We filled the compartments with a variety of nutrients such as agar, starch and gelatin, placed the tubes in racks and deposited the racks on the sea floor. With the aid of a baffle the rack was positioned so that the lower two compartments of the tubes were buried in the bottom sediment but the upper two were not.

After an incubation period of 12 to 15 months at our bottom stations the tube racks were retrieved. The exposed nutrient surfaces had been colonized by bacteria but showed very little bacterial decomposition. This was particularly true of the nutrients incubated in the tube compartments that had been below the surface of the bottom sediment. Where the access hole of a compartment was flush with the sediment surface or entirely exposed to seawater above the sediment, however, the nutrient surface bore extensive marks of animal feeding. Several compartments had actually been invaded by small mollusks (specifically bivalves) and by marine worms (polychaetes). Although such evidence was only semiquantitative, it clearly indicated that the feeding activity of deep-sea animals proceeded quickly.

This fact has also been demonstrated by workers at the Scripps Institution of Oceanography. John D. Isaacs has demonstrated by means of time-lapse photography that fishes appear soon after a bait has been placed on the deep-sea floor and that they consume the bait within days if not hours. Robert R. Hessler has observed the same quick response among crustaceans in deep-sea trenches, where fishes appeared to be absent.

To compare animal feeding with nutrient conversion in bacteria, however, is to confuse behavior with metabolism. Studies with bacteria enable us to measure directly the effect of deep-sea conditions on metabolic processes. Unlike even the simplest invertebrates, bacteria have neither a nervous system nor any complex patterns of behavior. Furthermore, they exhibit virtually no individual variations within a population. These attributes make bacteria unique among all organisms as a subject of quantitative, reproducible physiological experiments.

Studies of animal metabolism, as distinct from animal behavior, are more difficult to conduct and to interpret. Some preliminary results suggest that these advanced organisms are not entirely immune to the effects of high pressure. By catching a deep-sea fish in a Plexiglas trap on the ocean floor Kenneth L. Smith of the Scripps Institution was able to determine that the rate of its oxygen uptake in deep water was lower by two orders of magnitude than the rate of a shallow-water fish of comparable size. There is the possibility that the response of the fishes to being confined in a trap may have affected their metabolic rate.

Sanders and J. Frederick Grassle of Woods Hole have studied the fauna of the deep sea for many years and have concluded from various criteria, such as the low number of eggs produced and the apparent longevity of individual animals, that life processes in the deep sea must be slower than those in shallow water. This coincides with an observation made by Karl K. Turekian of Yale University, who has calculated from the ratios of isotopes in the shell of a small deep-sea bivalve that it was about 100 years old. Close relatives of this clam in shallow water are rarely older than two or three years and are never older than 10 years. It can be generally concluded that the life processes of animals as well as bacteria may be slower in the deep sea than they are in shallow water.

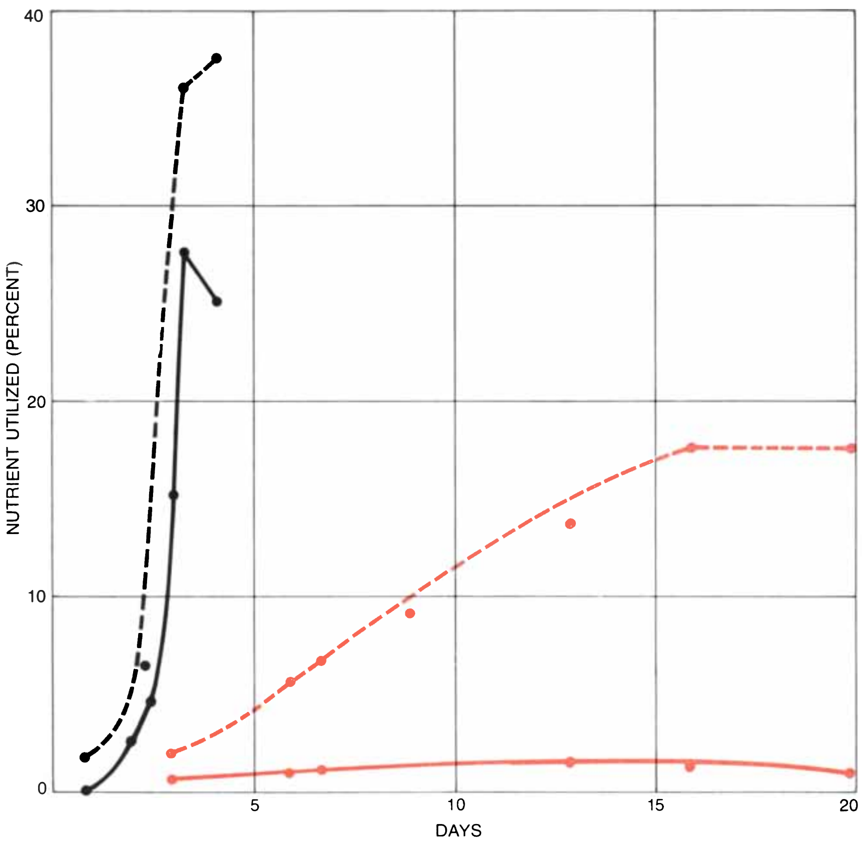
An interesting exception to this general picture is the observation made by Ruth D. Turner of Harvard University on wood-boring bivalves, which depend entirely on wood as a nonmarine food source. The rates of growth of such bivalves in the deep sea are similar to those of bivalves in shallow waters. Rather than following a survival strategy of energy saving and longevity of the individual organism, these organisms appear to consume their food source rapidly for the maximum production of progeny in the form of enormous quantities of eggs. In order to ensure the survival of the species a maximum production of progeny is a better strategy than the conservation of a rare resource. Dispersing eggs in enormous quantities improves the chance that at least some of the individuals in later generations will encounter another piece of wood and live to reproduce in their turn.

By analogy barophilic metabolism of bacteria may be considered an unfavorable evolutionary adaptation under conditions of low food supply. This argument does not hold, however, in cases where the survival of a species is based not on the growth efficiency and longevity of the individual cell but on the rapid production of large numbers of progeny. Compared with the elaborate food-finding and food-gathering capabilities developed in highly evolved organisms, the bacteria's only way to adapt to the environmental conditions of the deep sea appears to be the acquisition of barotolerance and psychrotolerance.

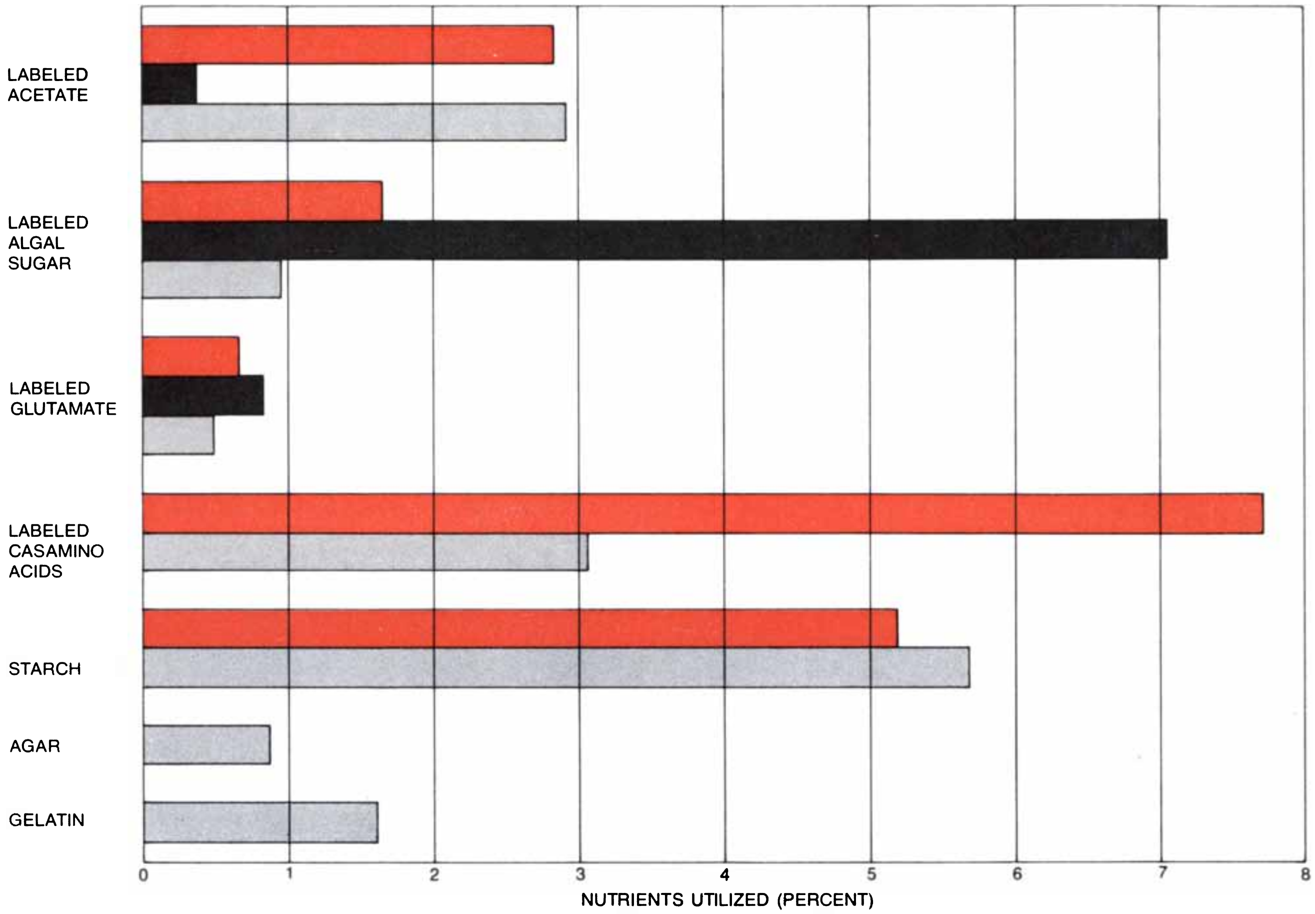
There is little information on what and how much material produced in surface waters reaches the deep sea. Small particles of organic matter sink so slowly we have good reason to assume that most of their readily degradable content has been removed before they arrive on the bottom. The least decomposed and therefore the most nutritious foods that reach the ocean floor must be large, fast-sinking objects such as fish carcasses. The principal scavengers of such material are not bacteria but animals, because of the animals' ability to locate food sources with their highly developed sense of smell. They are then able to move quickly to the scene and to ingest the food. Their feces, however, serve to spread the remnants of the organic matter across the sea floor, making the nutrients available both to the smaller, immobile animals and to the microorganisms that live in the bottom sediments.

There is also a continuous rain of fecal pellets produced by the zooplankton. These pellets are enveloped in a film of slime covered by bacteria that can grow on materials that cannot be digested by the zooplankton. On their long voyage to the deep sea the pellets may be eaten several times, and each time the bacteria, as producers of digestible food materials, are stripped off. How much organic matter is actually reaching the deep sea in this way is currently being studied with the aid of sediment traps. A particularly important function of bacteria in the food chain is their conversion of dissolved organic matter into bacterial cells, that is, into small food particles that can be consumed by filter-feeding animals.

In all these instances the primary producers, as the first link in the food chain, are plants. A variation on this theme, so far unique, was discovered early this year during a dive by the *Alvin* off the Galápagos Islands in the southeastern Pacific. The submersible was exploring certain submarine springs at a depth of about 2,700 meters along the Galápagos Rift. In the immediate area of the springs the crew observed an unusually dense population of large clams and other filter-feeding animals. The water



METABOLIC ACTIVITY of an undecompressed natural population of microbes collected at a depth of about 3,000 meters (*color*) was measured in the laboratory at the corresponding pressure of about 300 atmospheres. A control population (*black*) was measured at normal atmospheric pressure. Both populations of microbes were maintained at the deep-sea temperature of 3.5 degrees Celsius, and both were given a nutrient labeled with radioactive carbon. Respiration (*broken line*) and carbon uptake (*solid line*) are expressed as percentages of the nutrient utilized. Population that was kept under deep-sea pressure was 64 times slower in carbon uptake and 11 times slower in respiration than population that was kept under normal pressure.



DEEP-SEA INCUBATION of nutrient-filled bottles, inoculated with seawater and deposited on the ocean floor for between two months and a year, produced this record of microbial activity. Seven separate nutrients, four labeled with radioactive carbon, were treated in one or more of the following ways: inoculation at 200 meters followed by incubation at 5,300 meters (*colored bar*), inoculation at 200 meters followed by incubation at 1,830 meters (*black*) and inoculation at 1,830 meters followed by incubation at the same depth (*gray*). As experimental controls duplicate samples of seawater were added to the same nutrients in the laboratory and were incubated under normal pressure at a temperature of three degrees C. The metabolic activity of the natural populations of microbes incubated on the sea floor is expressed as a percentage of nutrients utilized based on unpressurized control populations over same period. The populations' responses varied greatly, but on the average deep-sea populations' activity was only 2.8 percent of that of the unpressurized controls.

near the springs had a milky appearance, and the water samples the *Alvin* carried back to the surface for analysis showed varying concentrations of dissolved oxygen and hydrogen sulfide.

The observations suggest that a phenomenon well known in shallow-water environments is taking place here in the deep sea: bacteria are getting the energy they need for their life processes from the metabolism not of organic substances but of inorganic ones. Given the presence of oxygen, the bacteria are able to oxidize the hydrogen sulfide in the spring water, a reaction that releases energy. The resulting abundant growth of bacteria, cast now in the role of primary producers, leads to the profuse growth of filter-feeding animals and other animals up the food chain. Hence this unusual oasis of abundant life in a deep-sea habitat finds its explanation in the fact that the primary product does not have to pass down from the surface to the sediment but is produced right on the spot for local consumption.

Although this phenomenon is most peculiar and intriguing, the deep-sea floor in most other parts of the world ocean resembles a desert as far as the abundance of food is concerned. It still needs to be confirmed that the scarce life at the bottom is supported by the limited supply of large chunks of rapidly sinking food materials.

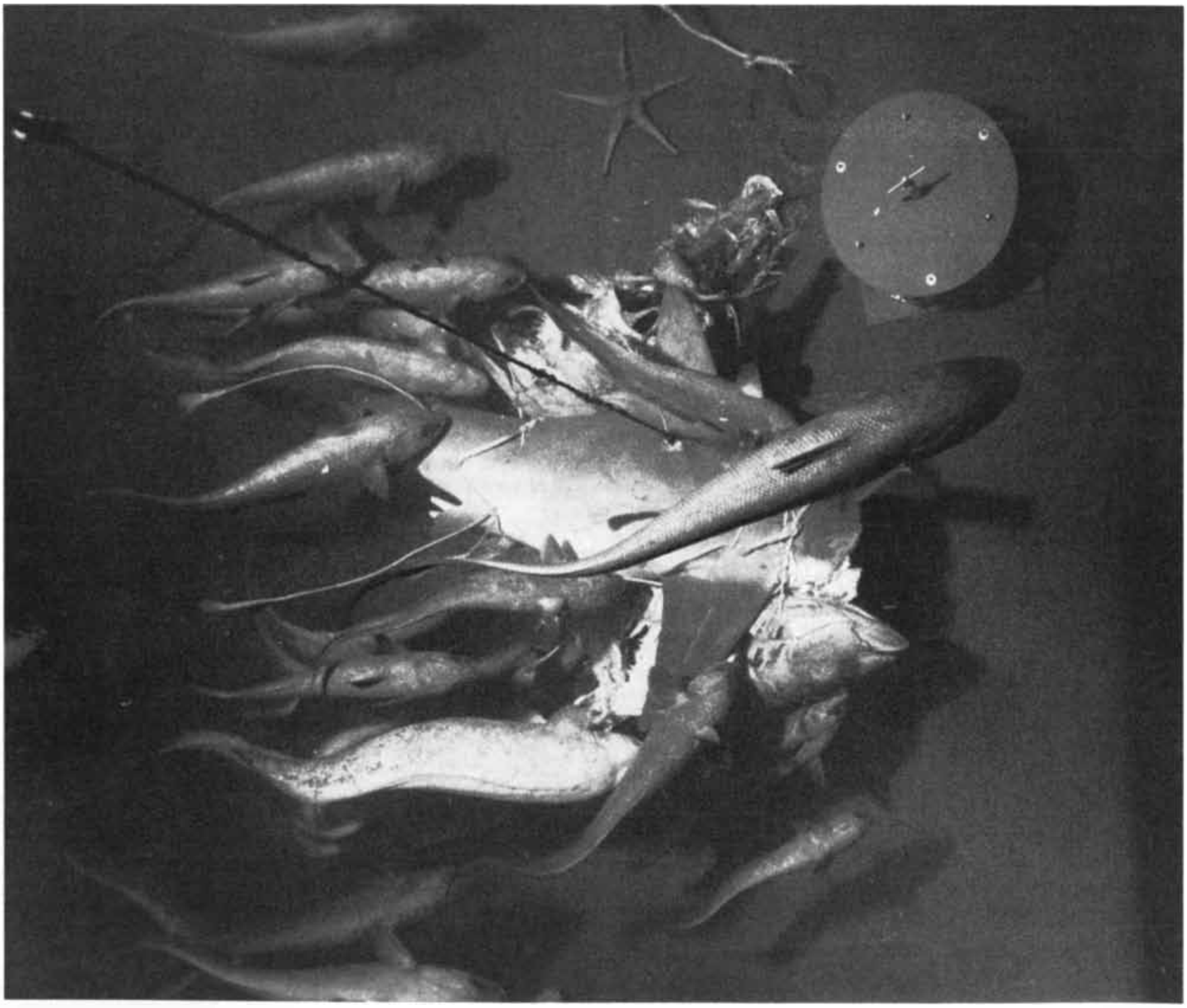
For years we have wanted to pursue this point by using a large bait, such as one of the whales that are occasionally stranded and die on the New England coast. If the beached carcass is large, the Coast Guard usually tows it out to sea for disposal, and we hope to arrange for the sinking of such a bait near one of our deep-sea stations. Meanwhile we have experimented on a smaller scale. Recently we sank a sizable fish sample, consisting of two tunas and one large shark, near Bottom Station No. 2, about 200 miles south of Nantucket. The Atlantic here is 3,640 meters deep. A recoverable camera, designed by Harold E. Edgerton of the Massachusetts Institute of Technology, was attached to a cable above the bait; it made pictures at 30-minute intervals for the next 16 days.

Nine days after the bait was planted we visited the site aboard the *Alvin*. Both tunas had been half-consumed but the shark remained unchanged. In the vicinity we observed a fair number of the kind of deep-sea fishes known as grenadiers, but they were not actively feeding. We saw only a few small crustaceans on the bottom; the fishes may have been keeping their number low. A later look at the photographs made it clear that our visit to the bait had disturbed the feeding animals. The abundance of the scavenger population attracted to the bait, their diversity and even some aspects of their behavior have now been photographically recorded [*see illustration on next page*]. Two of our colleagues at Woods Hole, Richard L. Haedrich and Gilbert T. Rowe, are engaged in analyzing this record.

Near the bait we deposited a trap containing radioactively labeled fish meat to capture some of the crustaceans that had been attracted by the big bait. If the crustaceans are trapped and consume the labeled meat, we should be able to learn something about their metabolic rate. On the same dive we began an experiment to study decomposition processes involving organisms of intermediate size. The apparatus is simple: a pair of Plexiglas boxes, each with four compartments [*see bottom illustration on page 43*]. Each compartment contains the same variety of solid food materials. The compartments are closed with nylon screen of mesh sizes from .03 millimeter to 12 millimeters, a range that admits a large variety of feeding organisms. On this particular 11-hour dive we handled procedures for nine different experiments.

Our experiments studying the microbial activity in the deep sea began with the original observation on the *Alvin* box lunch and proceeded from the in situ incubations on deep-sea moorings to in situ inoculations with the aid of the *Alvin* and finally to the development of pressure and temperature equipment for more sophisticated laboratory studies. All the data obtained with natural populations indicated a reduction of metabolic activities under deep-sea conditions. Compared with the elaborate food-finding and gathering capabilities developed in highly evolved organisms, the bacteria's only way of adapting to the environmental conditions of the deep sea appears to be their acquisition of psychrotolerance and barotolerance. The logical next step is to obtain pure cultures of undecompressed bacteria from the deep sea, since there is still the possibility that truly barophilic bacteria escape detection in our present experiments. Pure cultures will also enable us to study the degree and nature of barotolerance. Work on the molecular basis of pressure effects in microorganisms is being done in the laboratory of Joseph V. Landau and Daniel H. Pope at the Rensselaer Polytechnic Institute. Similar work with undecompressed cultures of deep-sea bacteria will be of much interest.

In retrospect it appears that if the *Alvin* sandwich had not been properly kept in a lunch box, fishes and crustaceans would have eaten it and microorganisms would not have had a chance. Nor, for that matter, would microbiologists.



DEEP-SEA DEGRADATION STUDIES are seen in progress at the Woods Hole Bottom Station No. 2, which is at a depth of 3,640 meters some 200 miles south of Nantucket Island. An automatic camera makes photographs at 30-minute intervals over a 17-day period following the depositing on the bottom of a bait consisting of two tunas and a shark. This photograph was made on the 15th day; little is left of the tunas but the shark has not yet been touched by the scavengers. Most of the fishes around the bait are grenadiers (*Coryphaenoides armatus*). The larger fish at the bottom is a brotulid (*Parabassogigas crassus*). The round object at the upper right is the top of a baited trap that was set in position by the authors when they visited the site aboard the *Alvin*. It is baited with radioactively labeled fish meat and will admit small animals such as the scavenging crustaceans known as amphipods. The retrieval of traps like this one after they have been on the sea floor for various periods of time will allow metabolic studies both of the amphipods and of their gut bacteria.

Direct photography by infrared alone, 1932

But for sources cooler than 250° C, something besides the right film is needed even in 1977

If the night is completely dark and your roof can be directly photographed on infrared film, call the fire department.

Year in and year out we get inquiries for thermal photography film. Sorry, but at wavelengths beyond 1.3 μm the photons continue to lack the poop to create a latent image. Even if we punched our way out of that limitation, the means that would be required to keep everything else sufficiently colder than the subject would probably be more elaborate than currently available indirect methods of thermal photography.

But if your subject is not much below 250°C (incandescence begins around 500°C), you have good prospects for tonal rendition of temperature differences if you photograph in complete visual darkness. You'll need a sturdy tripod for exposures that are as apt to run to hours as seconds, even if you are using KODAK High Speed Infrared Film 2481 (ESTAR Base) at *f*/1.9. For thermometry by such photography, you expose on the same roll of film a series of shots of a hot object held successively at known temperatures. Then you calibrate by plotting density against temperature for a given exposure. If temperature over the subject ranges over more than 120°C, it is well to make a long exposure for the cooler parts and a shorter one for the hotter areas. With a range of 60°C or less, differences of 15°C are distinguishable.

Below 250°C, to see temperature differences from a distance, you will need some kind of electronic device to put an image on a CRT, from which you record photographically. Without spending that kind of money, another line of our products can be useful in thermography right down to room temperature, provided the subject is one on which you can coat some washable black paint followed by a cholesteric liquid-crystal mixture formulated to go through a series of sharp color changes over a given temperature range that can be as short as 5°C. A meaningful record on color film can be obtained by use of a polarizing filter over the light source and care not to vary the camera and light angles between shots.

See your regular photo supplier for the film and filters. Ask Kodak, Dept. 55W, Rochester, N.Y. 14650 for Kodak Publication JJ-14, "EASTMAN Liquid Crystal Products," if interested in that subject.

Anyway, more people want to photograph wedding parties than hot chimneys

Just now being introduced is KODACOLOR 400 Film. With that behind a lens at *f*/2 and a shutter operating at 1/30 sec, you can probably forget flash at the illumination level typical of the American evening at home when not watching TV—around 5 footcandles. To record festivity in the June sunshine, use KODACOLOR II Film if you plan on big enlargements. You may prefer the way it now renders fabric colors, and speed has been boosted to 100 to make underexposure a little less likely while risk of overexposure remains generally negligible. Also broader now in both films is the tolerance for differences in spectral quality of illuminants, as between daylight, fluorescents, and tungsten. Another improvement will not be noticed for a long time: dye stability in negatives kept under proper dark storage.

Kodak

SCIENCE AND THE CITIZEN

Deep Six Hundred

The redefinition of the future role of the U.S. nuclear power program implicit in President Carter's national energy policy has been widely interpreted as a major step away from projections that had placed the fission process at the center of the long-term U.S. energy budget. In keeping with his campaign pledge to consider nuclear power only as the energy source of "last resort" the President has evidently decided to indefinitely defer plans for the commercial reprocessing and recycling of spent nuclear fuel, to de-emphasize the U.S. fast-breeder-reactor program and to redirect research efforts toward the investigation of inherently less resource-efficient (but more "proliferation-resistant") alternative nuclear-fuel cycles and reactor designs.

On the other hand, there are indications that the Carter approach to nuclear power involves affirmative steps as well. For example, the new program calls explicitly for the use of "increasing amounts of nuclear energy," the improvement of the Federal program for evaluating national uranium (and now thorium) resources, the expansion of this country's uranium-enrichment capacity (with particular emphasis on the development of centrifuge technology), the establishment of "reasonable, objective criteria" for the licensing of nuclear power plants that are based on standardized light-water-reactor designs and the enforcement of more effective safety standards. Moreover, for the "tail end" of the nuclear-fuel cycle the Administration's policy stresses the need for "more adequate storage for spent fuel supplies."

On this last score the prospects for early success appear quite favorable. As Bernard L. Cohen of the University of Pittsburgh explains elsewhere in this issue (see "The Disposal of Radioactive Wastes from Fission Reactors," page 21), a satisfactory solution to the nuclear-waste-disposal problem is at hand: there appears to be wide agreement among U.S. nuclear-power experts that no great technical or economic obstacle stands in the way of the long-discussed plan for storing the solidified radioactive wastes from nuclear-power reactors in secure repositories some 600 meters underground in geologically stable rock formations.

In spite of the fact that the idea of burying such high-level wastes in deep underground repositories has been subjected to detailed analysis for more than 20 years, Cohen says, "the development of suitable burial sites has not gone smoothly." In the 1960's workers from the Oak Ridge National Laboratory, organized in Project Salt Vault, conducted a series of experiments on radiation and heating effects in a salt mine near Lyons, Kan. For a time the mine was a prime candidate for the site of the first Federally operated deep underground waste repository. Earlier oil prospecting in the area, however, had left many drill holes through the formation, and in the course of nearby salt-mining operations based on dissolving the salt in water it was found that a considerable amount of the water could not be accounted for, leaving open the possibility that there might be cracks in the salt formation through which water might reach the buried wastes. As a result of these findings (and a good deal of adverse publicity accompanying them) the Kansas site was finally abandoned and a new search was begun for suitable formations.

The most promising burial site found so far is in southeastern New Mexico, where at least three exploratory holes have already been drilled to study the characteristics of the salt beds. Last year a new Office of Waste Isolation, with headquarters at Oak Ridge, was established by the Energy Research and Development Administration (ERDA) to direct the deep-burial project. Assuming that everything goes according to plan, the site is expected to be ready to receive its first shipments of high-level nuclear wastes by 1985.

A complicating aspect of the nuclear-waste-disposal problem is represented by the large quantities of radioactive wastes generated by the U.S. nuclear-weapons program. High-level wastes resulting from the production of plutonium and from various other weapons operations are currently stored in comparatively shallow underground tanks adjacent to Federally operated fuel-reprocessing plants at Hanford, Wash., Idaho Falls, Idaho, and Aiken, S.C. Because of the less efficient chemical-reprocessing techniques employed in former years, and because of the shorter fuel "burn-up" time required for producing weapons-grade plutonium, the military wastes are more than an order of magnitude less concentrated than the high-level wastes that would result from the operation of commercial nuclear power plants. Moreover, the acidity of the military wastes has been neutralized, increasing their bulk and complicating the task of incorporating them into more easily disposable solid-glass cylinders.

Since military programs are not subject to the stringent environmental reviews and other constraints of civilian programs, Cohen remarks, "the care taken of the military wastes has been something less than exemplary." For example, in recent years there has been much publicity about leaks in the storage tanks for liquid radioactive wastes at the Hanford site. In the 151 tanks there a total of 16 leaks have been discovered, the largest involving the release of 115,000 gallons of waste solution, including 40,000 curies of cesium 137, 14,000 curies of strontium 90 and four curies of plutonium, all of which are considered particularly dangerous isotopes.

An investigation of the largest leak at the Hanford site has indicated that some of the radioactivity has gone as far as 47 feet below the tank, leaving it still about 120 feet above the water table in this arid area. The potentially troublesome isotopes of cesium, strontium and plutonium, however, have penetrated only a few feet below the tank. Hydrologists estimate that the flow of ground water in the area is such that it would take water from directly under the burial site some 800 years to reach the Columbia River, 10 miles away. Owing to the phenomenon of ion-exchange holdup, however, the more dangerous radioactive materials would move much more slowly than the ground water, with the result that the radioactive cesium, strontium and plutonium isotopes would decay to such an extent that even if they reached the water table and entered the river, they would not be a threat to human health.

In Cohen's view "it is difficult to devise scenarios in which the leaks that have occurred could affect human health. For example, if four curies of plutonium 239 were to be dissolved directly into the river, one would expect only about .00006 curie to be ingested by humans, and this amount would have only about one chance in 6,000 of causing a single cancer. Even if the plutonium were somehow to be distributed uniformly through the top 40 feet of soil (the bottom of the storage tank is 40 feet below ground level), and the soil were to be used continuously for growing food, there would still be only about one chance in 20 that a single cancer would ever result."

Cohen points out that several measures have already been taken to eliminate the problem of the leaking storage tanks. Most important, in his opinion, is the use of double walls, "so that if leaks appear in the inner wall, they can be promptly detected and the liquid, which is still contained, can be pumped out into standby tanks that are always avail-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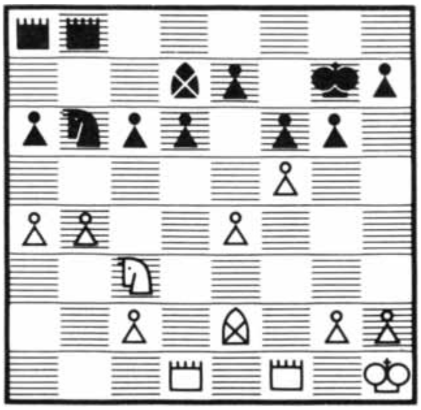
able." All the storage tanks for high-level wastes in the U.S. except the older ones at Hanford are double-walled. The military wastes are now in the process of being converted into a wet solid inside the tanks, a stratagem that will eliminate leakage through cracks and small holes such as those that caused the previous leaks. This solidification program is now more than half completed, and present indications are that it will be finished by 1980. A study is currently under way to develop alternatives for the final disposition of the solidified material, and a report on the matter is due later this year. There is some sentiment among the members of the study group, Cohen reports, that in solidified form the wastes are "not sufficiently dangerous to warrant management equivalent to that planned for commercial high-level wastes."

At the moment the only commercial high-level wastes in the U.S. are stored in double-walled underground tanks at the site of a shut-down commercial reprocessing plant in West Valley, N.Y. The wastes there total 570,000 gallons in the form of a neutralized solution, plus 30,000 gallons of highly radioactive sludge, which has settled to the bottom of the tanks. In addition 12,000 gallons of a different kind of waste from an experimental reactor is stored in a separate tank. Periodic inspections have indicated that there has been no appreciable corrosion of the walls of the tanks, and a spare tank is available in case the inner walls of the present storage tanks develop leaks; Cohen concurs in the view that under these circumstances the final disposal of these wastes is not an urgent problem. Nevertheless, a study of various alternatives for disposing of the West Valley wastes was published in 1976, and a decision among these alternatives is pending. The costs of the various approaches are estimated to range up to several hundred million 1975 dollars and the delay times before permanent disposal to vary between seven and 20 years. "By then," Cohen observes, "the program for permanent burial of wastes in deep subterranean repositories should be in routine operation."

LEVY/BLACK



CHESS 4.5/WHITE
POSITION AFTER 26. P-QR4??

1.	P-K4	P-QB4	23.	R-QN1	N-N3
2.	N-KB3	P-Q3	24.	R/B3-B1	R/B-QN1
3.	P-Q4	P×P	25.	R/N-Q1	P-B3!
4.	N×P	N-KB3	26.	P-QR4??	P-QR4!
5.	N-QB3	P-KN3	27.	P-N5	P×P/N4
6.	P-B3	B-N2	28.	P×P/N5	R-QB1
7.	B-K3	O-O	29.	R-Q3	R-B4
8.	Q-Q2	N-B3	30.	R-N3	R/R-QB1
9.	B-QB4	P-QR3	31.	R/1-B3	P-R5
10.	N×N?	P×N	32.	P-R4	P-R6
11.	O-O	N-Q2	33.	P×P	P×P
12.	P-B4	N-N3	34.	R-K3	B-K3
13.	B-K2	B-K3	35.	P-R5	P-N4
14.	P-QN3	N-B1	36.	N-Q5	P-R7
15.	P-QR3!	Q-R4	37.	R-QR3	B×N
16.	P-QN4	Q-B2	38.	P×B	R×P/B7
17.	P-B5!	B-Q2	39.	B-Q1	R-Q7
18.	B-R6	Q-N3 ch!	40.	K-R2	R-B8
19.	K-R1	Q-Q5	41.	B-N3	P-R8=Q
20.	Q×Q	B×Q	42.	R×Q	R×R
21.	R-B3	B-N2	43.	Resigns	
22.	B×B	K×B			

Chess 4.5 (White) v. David Levy (Black)

Good Try

In August, 1968, David Levy, then the chess champion of Scotland and subsequently an international chess master, made a bet of 1,250 pounds (about $2,100) with four computer scientists that no computer would be able to beat him in a chess match of an even number of games within the next 10 years. The first official game was played this spring in Pittsburgh, when Levy sat down across the board from Chess 4.5, holder of the U.S. computer-chess title and generally considered to be the best chess program yet devised. Chess 4.5 was programmed to run on the world's most powerful commercial computer; the Cyber 176 built by the Control Data Corporation. After three and a half hours of close play and Levy's 42nd move the machine "resigned." The actual decision to resign was made by the program's developers, Lawrence R. Atkin and David J. Slate of the Computation Center at Northwestern University, who took turns transmitting Levy's moves to the Minneapolis-based computer through a terminal at Carnegie-Mellon University, where the game was played.

Chess 4.5 is the latest version of a program Atkin and Slate began developing in their spare time in 1969 (with early help from Keith Gorlen). Last summer the Chess 4.5–Cyber 176 combination won the Paul Masson Class B Championship, the first victory of a computer in a human tournament. In March, 1977, Chess 4.5 won the Minnesota Open Championship, in which the computer's opponents were ranked either Class A or "expert." On the official ranking scale a Class A player has a numerical rating between 1,800 and 1,999; an expert has a rating between 2,000 and 2,199. The rating of Anatoly Karpov, the current world chess champion, is 2,690. Levy's rating is 2,325.

The Atkin-Slate team thought the time had come for Chess 4.5 to challenge Levy, even though the odds of its winning a two-game match were reckoned to be no better than one in 100. The following account is based on an analysis made by Hans Berliner, a computer scientist at Carnegie-Mellon and a former holder of the world correspondence-chess championship. Berliner described the moves on a demonstration board during the game. The players were required to make 40 moves in two hours, which are the usual conditions for match play.

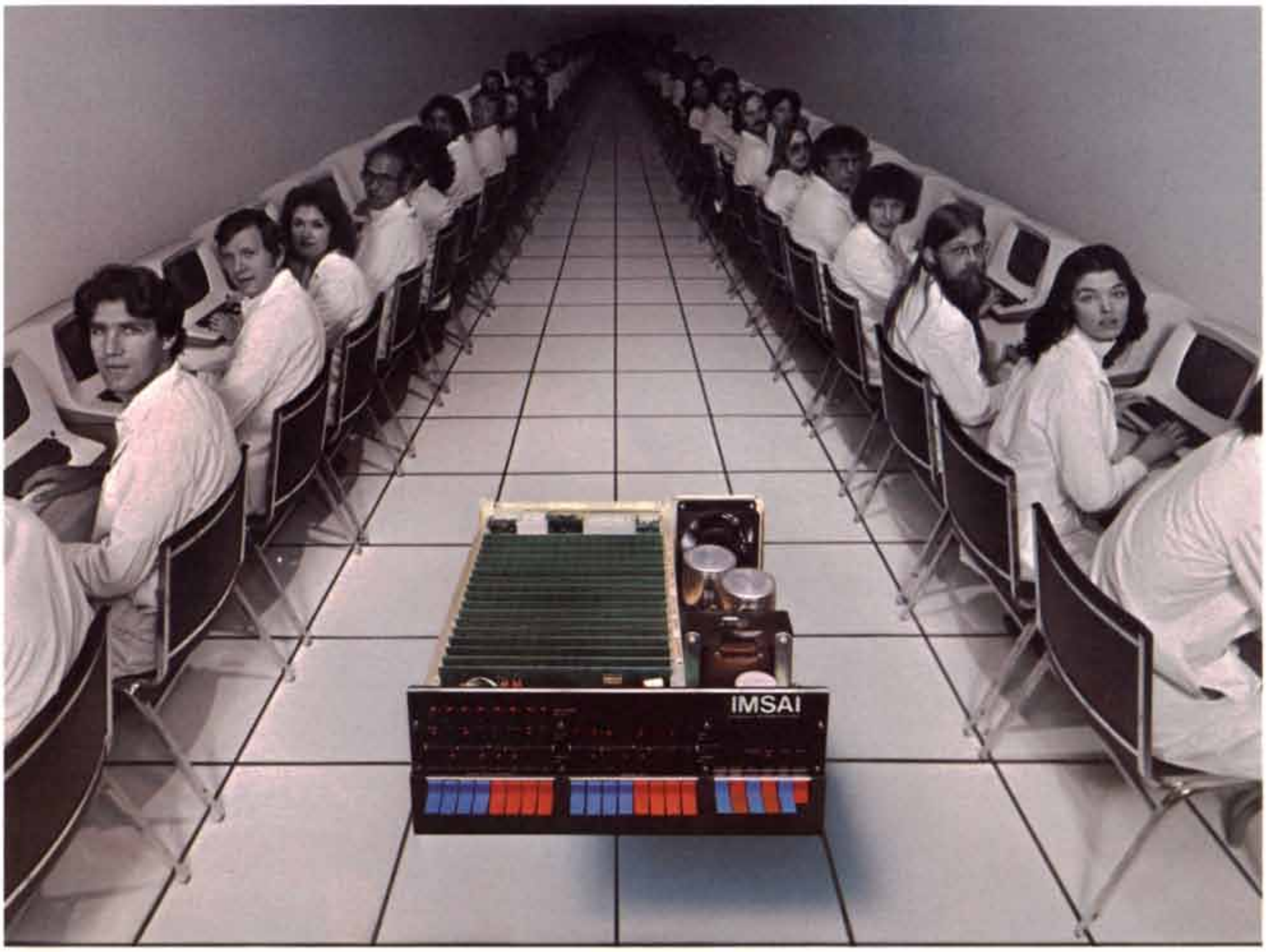
Levy won the toss of the coin and elected to play Black. Atkin informed the computer it was playing White and asked it to make the first move. The move was pawn to king 4 (P-K4); Levy responded with a variation of the familiar Dragon variation, which normally leads to a good battle (*see illustration on this page*). In selecting its early moves the computer chooses from a "book" of standard openings stored in its memory. Move No. 9, bishop to queen's bishop 4 (B-QB4), was added to Chess 4.5's book just before the match because a more familiar move (castling on the queen side) had occasionally given the computer trouble.

Chess 4.5's capture of Levy's knight on move No. 10 (NxN) was a serious error because it strengthened Black's center. Move 15 (P-QR3) was awarded an exclamation point by Berliner because it correctly anticipated and blunted the effect of Levy's threat in moving his queen to rook 4 (...Q-R4). By the 17th move Chess 4.5 had gained a slight upper hand. With move No. 18, bishop to rook 6 (B-R6), however, Chess 4.5 misjudged the situation and allowed the exchange of queens two moves later, considerably relieving Levy's position. At this point the game was even. Chess 4.5 could have retained its advantage at No. 18 by moving its rook to bishop 3 (R-B3), thereby preparing the way for a strong attack by moving its bishop to rook 6 (B-R6).

On the 26th move Chess 4.5 made a grievous error (P-QR4??), which ruined its pawn structure on the queen side. After that the outcome was no longer in doubt. With 17 more moves Levy forced the resignation.

At the conclusion of the regular game Levy and Chess 4.5 played a "blitz" game in which each side was allowed only five seconds per move. In this con-

POWER.



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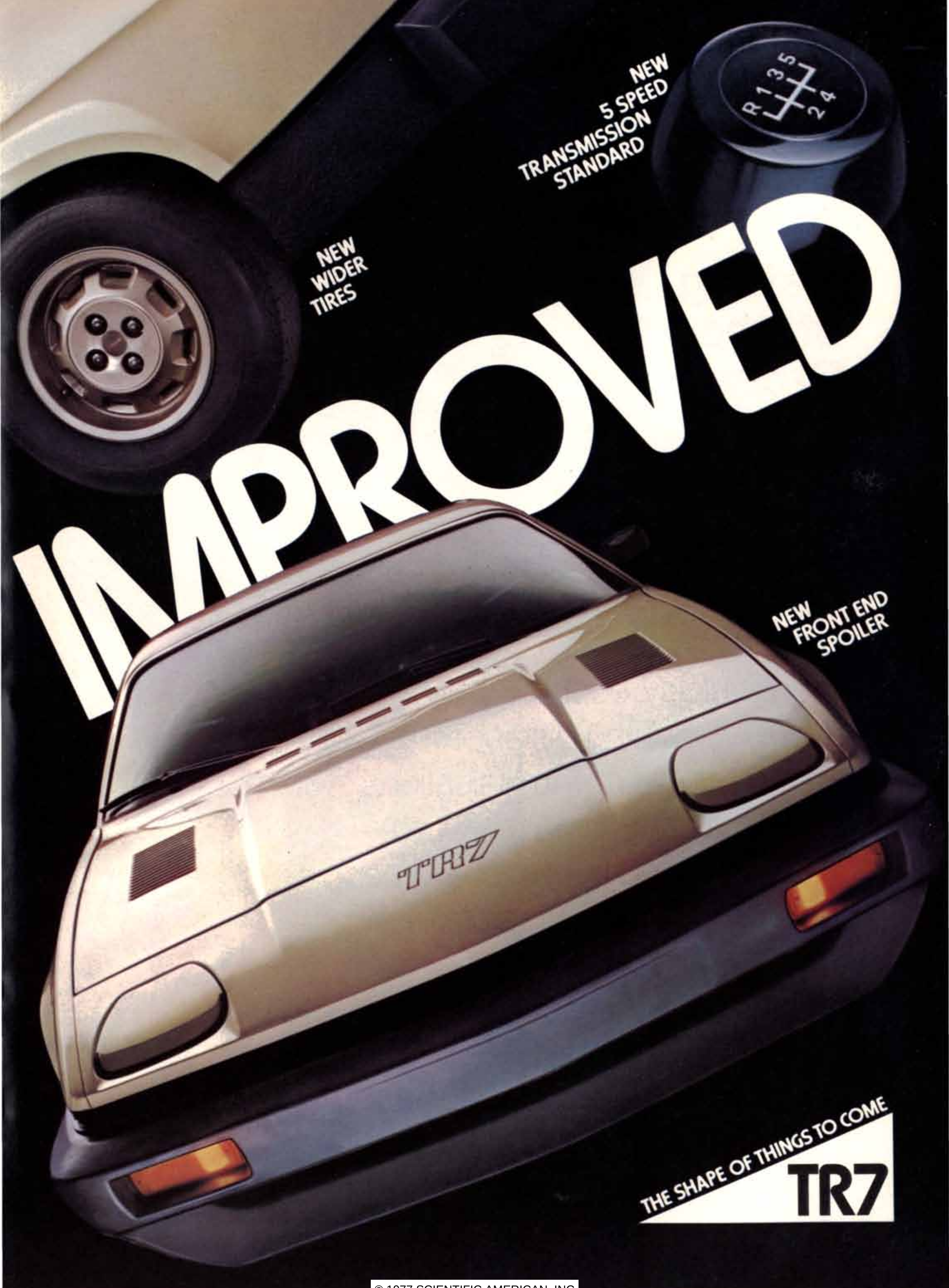
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test Chess 4.5 quickly gained the advantage, and Levy resigned on his 38th move. Berliner estimates that in blitz chess the computer improves its rating by 200 or 400 points over a human opponent. With the loss to Levy in the regulation-time game Chess 4.5's first challenge was ended. Its developers now have somewhat more than a year to make further improvements in the program and to decide whether or not to issue a new challenge. In the meantime there may be challenges from other programs.

Unequal Time

An Indiana judge has ruled that the use in public schools of a biology textbook espousing the biblical doctrine of special creation and denigrating evolution violates state law, the Indiana constitution and the first amendment of the U.S. Constitution. He based his decision primarily on a finding that the text seeks to promote "fundamentalist Christian doctrine in the public schools" by presenting creationism "as the only accepted scientific theory." The book, *Biology: A Search for Order in Complexity,* had been approved in 1975 by the Indiana textbook commission and had been adopted by seven school districts, in two of which it was the only ninth-grade biology textbook. The Indiana Civil Liberties Union, acting on behalf of a student and parents in one of the sole-adoption districts, got a court order requiring a rehearing by the commission, which reaffirmed its approval of the textbook; the ICLU thereupon went to court to appeal the commission's decision.

Judge Michael T. Dugan reviewed the hearing record and examined the text and its teacher's guide. In his decision Dugan quoted the book's preface to the effect that "it is explicit throughout the text that the most reasonable explanation for the actual facts of biology as they are known scientifically is that of biblical creationism." The text conforms to that description, he found; for example, two chapters "are devoted to lengthy discussions of the fallacies and weaknesses of the evolution viewpoint," whereas "there are no chapters or passages in the text which deal critically" with creationism. Any idea of fairness, he held, "is dispelled by the demand for 'correct' Christian answers" in the teacher's guide. Citing constitutional barriers and also an Indiana law forbidding the approval of "a textbook which contains anything of a partisan or sectarian character," Dugan reversed the commission's findings in approving the book. By not limiting his decision to the sole-adoption districts, Dugan apparently said that no sectarian book could be adopted as a textbook, even if it is read in conjunction with another text; the decision presumably does not limit the choice of books for a school library or as supplementary reading in class.

Biology: A Search for Order in Complexity was published in 1974 by the Zondervan Publishing House of Grand Rapids, Mich., and has sold about 50,000 copies, most of them in privately supported schools that teach fundamentalist Christian principles. It was written and edited by members of the Creation Research Society and has been promoted in the public schools by the loosely related Creation Life Publishers. The text has been approved by state commissions in Alabama, Georgia, Oklahoma and Oregon; it has been adopted as an alternative text in Dallas, even though it has not been approved in Texas.

Earlier Americans

Long-term archaeological studies at sites in Illinois, Pennsylvania and California are helping to assemble various bits and pieces of North American prehistory into a more coherent chronological whole. Working backward from the first millennium B.C., Stuart Struever of Northwestern University and his co-workers have been probing the Koster site in southern Illinois since 1969. Their excavations at this remarkably deep stratified site have continued to produce a wealth of information about residents of the valley of the lower Illinois River during some 4,000 years of the Archaic period. They have exposed or sampled more than seven successive Archaic living floors; the earliest was apparently occupied in about 7000 B.C. Two even deeper levels have been identified, although not yet dated, and the workers at the site have yet to reach levels that show no trace of human occupation.

The people of the Archaic period, to judge from the remains at other New World Archaic sites, were hunters and gatherers. It has therefore been generally assumed that they moved their encampments with the seasons. The evidence at Koster, however, suggests a more sedentary way of life. For example, a living floor occupied in about 6500 B.C. contains postholes, evidence of the presence of timber uprights, although no structural pattern is apparent. Levels occupied from 5000 B.C. onward, however, show posthole patterns clearly indicative of dwellings, and the remains of foodstuffs show the utilization of nonseasonal resources such as mussels and fish. Many of the fish were only an inch long; their size suggests that the residents worked in groups to harvest the fish in local ponds. The domesticated dog was present at Koster, and evidently not just for eating. At the level occupied in about 6500 B.C. the excavators found the remains of three dogs, each of which had been buried in an individual grave.

The Archaic period came to a close some 3,000 years ago. When did it begin? The question will remain open at least until Struever and his co-workers reach the bottom at Koster.

The culture of those who lived in America before the start of the Archaic period is known as Paleo-Indian. Its existence was not known until the second quarter of this century, when distinctive pressure-flaked projectile points were discovered in association first with the remains of an extinct bison (at Folsom, N.Mex., in 1925) and then with those of a mammoth (at Clovis, N.Mex., in 1932). Since then a number of similar Paleo-Indian kill and butchering sites have been recognized, most of them west of the Mississippi. Only recently, however, has investigation revealed a Paleo-Indian site that was occupied successively rather than on a single occasion.

This is the Meadowcroft site, a rock-shelter near Avella, Pa., where James Adovasio of the University of Pittsburgh and his associates began digging in 1973. Whereas the Folsom find is believed to date back to about 8000 B.C. and the Clovis find to about 10,000 B.C., the Meadowcroft shelter was occupied as early as 14,000 B.C. Moreover, Adovasio considers that an initial occupation date of about 20,000 B.C. is not improbable.

Like similar rock-shelters in the Old World, the Meadowcroft site was not occupied continuously but evidently served as a seasonal way station for Paleo-Indians on the move. People used the shelter during the Archaic period; their camp was occupied in about 3500 B.C. The last Paleo-Indian visits seem to have been in about 9000 or 8000 B.C. The visitors killed game; the largest identified remains are those of the elk. They also seem to have been hardworking seed collectors: carbonized and uncarbonized seeds representing 40 different edible varieties have been identified.

The oldest stone artifact yet unearthed at Meadowcroft is a relatively crude "knife" made by removing flakes from only one side of a chert cobble. Similar unifacial knives are known from later Paleo-Indian sites. Like many of the other stone tools from Meadowcroft, the knife was made out of a kind of chert that is not locally available.

What about still earlier Americans? One of the eight Santa Barbara Islands off the coast of southern California, Santa Rosa, has long been known for the remains of pygmy mammoths found there. Because some of the mammoth skulls show signs of damage, it has been suggested that residents of the area in the days when the Santa Barbara Islands were part of the mainland preyed on these long extinct animals. What has remained an open question is exactly when such hunts might have taken place.

Recently what appeared to be a cooking site on Santa Rosa was found by John Woolley, one of the owners of the island. Rainer Berger of the University of California at Los Angeles began to excavate the site in 1976 and has now announced the results of carbon-14 analyses of four charcoal samples from a hearth that contained the leg bone of a pigmy mammoth. No detectable traces of carbon 14 were found in the charcoal. This suggests that the fire was kindled at least 40,000 years ago, the span of time needed for the radioactive carbon to have decayed to nearly the vanishing point.

Berger found what are by Paleolithic standards rather advanced stone tools in the hearth area; they suggest that the site was used for both butchering and cooking. Noting that Santa Rosa represents the first association of a hearth, mammoth remains and human artifacts, Berger says he will try to apply refined techniques capable of detecting 50,000-year-old traces of carbon 14 to other samples from the hearth.

The Free-Electron Laser

A laser reduced to its essential form is an electron oscillator; it works by inducing identical motions in a great many electrons. In a real laser that underlying simplicity is often obscured because the electrons employed by the oscillator are those bound up in the intricate structure of atoms or molecules. Now a laser has been built and operated in which those complications are eliminated. It employs as a laser medium a beam of electrons in a vacuum.

The medium of a conventional laser is a population of atoms or molecules that can be "pumped" by an external source of energy to an excited state. Laser action begins when a few of the atoms or molecules fall to a state of lower energy by emitting a photon, or quantum of electromagnetic radiation. Some of the emitted photons are trapped in an optical "cavity" formed by a pair of mirrors, and as the photons bounce back and forth through the laser medium they stimulate other excited atoms or molecules to emit radiation of the same frequency and phase. Partial transmission by one of the mirrors allows some of the radiation to escape as a coherent beam.

When an atom absorbs or emits radiation, it does so by changing the state of motion of a bound electron. One of the basic premises of quantum mechanics is that the electrons in an atom can have only certain discrete modes of motion

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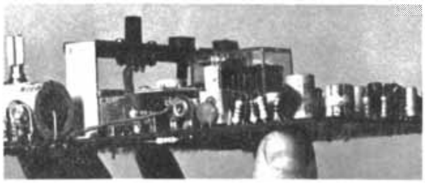

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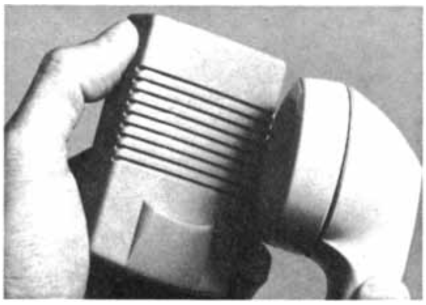

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and therefore the atom can have only discrete energy levels; intermediate states are forbidden. The atom can absorb or emit only those photons whose energies correspond to the difference in energy between two allowed states.

Because of the constraints on the motion of electrons in atoms, most lasers have a single characteristic wavelength that cannot readily be altered. The most important exceptions are lasers whose operating medium is an organic dye, a molecule with a series of absorption and emission lines so closely spaced they amount to a continuum. Dye lasers can be tuned to any wavelength within the continuum. For any single dye, however, that is a comparatively narrow range. Moreover, dye lasers cannot radiate very large amounts of power.

An unbound electron is not under the same constraints as an electron in an atom; a free electron can have practically any state of motion and any energy. Since an electron emits radiation whenever it changes its state of motion (that is, whenever it is accelerated), a free electron can radiate at any wavelength. That capacity for infinitely adjustable emission is exploited in many of the electron oscillators employed to generate radio waves and microwaves. The free-electron laser could provide the same ability to tune with the turn of a knob at optical wavelengths.

The prototype free-electron laser was recently constructed by John M. J. Madey of Stanford University and a group of his colleagues that includes David A. G. Deacon, Luis R. Elias, Gerald J. Ramian, H. Alan Schwettman and Todd I. Smith. They report their results in *Physical Review Letters.*

The heart of the laser is a superconducting magnet about five meters long wound in the form of a double helix with one turn about every three centimeters. The field produced by the magnet has the form of a corkscrew. Electrons supplied by the superconducting linear electron accelerator at Stanford are directed through a vacuum chamber inside the magnet winding. Radiation is emitted when the electrons encounter the magnetic field, which forces them to follow helical trajectories. What is first emitted is spontaneous radiation rather than the stimulated radiation characteristic of laser operation. The stimulated radiation appears when some of the spontaneously emitted photons are reflected and interact again with the moving electrons.

Electrons are supplied by the accelerator in "bunches" about a millimeter long, and the laser operates only during the brief intervals when a bunch of electrons is within the magnetic field. Thus the laser emission consists of a train of brief pulses of light, each about a millimeter long. The wavelength emitted is determined by the strength and geometry of the magnetic field and by the energy of the electrons; both of those quantities are potentially under the control of the experimenter.

Laser operation was demonstrated in the Stanford machine with a magnetic field of 2.4 kilogauss and with electrons that had an energy of 43.5 million electron volts. The resulting laser radiation was at a wavelength of 34,170 angstroms, in the infrared region of the electromagnetic spectrum. The average power of the external radiation was .36 watt, but that low power mainly reflects the fact that the laser was off most of the time (between bunches). The peak radiation field within the laser cavity was about 500 kilowatts.

The main reason for interest in the free-electron laser, beyond its elegant demonstration of physical principles, is the convenience with which it can be tuned over a broad band of wavelengths. Operation at short wavelengths is limited by a requirement for ever denser bunches of electrons, but wavelengths as short as 1,200 angstroms could probably be attained in a machine that could be built today. Such a machine would be a source of intense, monochromatic radiation that could be tuned at will to virtually any wavelength in the infrared, in the visible spectrum or in the ultraviolet.

Burning Question

A durable legend has it that in 212 B.C., during the siege of Syracuse by the Roman consul Marcus Claudius Marcellus in the Second Punic War, the defenders set fire to a Roman fleet by focusing the sun's rays on the wooden ships by means of a burning mirror that had been designed by Archimedes. Since the 17th century, when the properties of burning mirrors became better known, scholars in nearly every generation have been moved to prove or disprove the legend. In a recent issue of the journal *Technology and Culture* D. L. Simms has reexamined the available historical and technical facts to try to determine whether or not the legend could be true.

According to Simms, the earliest known unequivocal statement that Archimedes set fire to the Roman ships by focusing the sun's rays on them is a single sentence written by Anthemius of Tralles 700 years after the event. Anthemius refers only to the "unanimous tradition that Archimedes used burning mirrors to burn the enemy fleet a bowshot off." Neither the historian Polybius (who wrote when some of the combatants at Syracuse were still alive) nor Livy and Plutarch (who wrote in great detail about Archimedes' role in the siege of Syracuse) mention any form of fire employed as a weapon in the battle, let alone fire started by a burning mirror. "The historical evidence for Archimedes' burning mirrors is feeble, contradictory in itself," writes Simms. "Very late authorities for the story are unreliable, while the standard and contemporary [authorities are] silent."

Simms also questioned whether or not Archimedes had enough information available to him to design a burning mirror that would work. Assuming that the mirror would have been large enough to gather enough solar energy for the purpose, it would have to have had a parabolic form and a focal length of some 100 or 150 feet in order to focus a hot spot on a ship a bowshot away. Moreover, the focal length would probably have had to have been variable, or else the hot spot could not have been focused on a ship long enough to set it afire unless the ship accidentally happened to be precisely in range and standing still. The only known way of building a large mirror with a variable focus is to have an array of small flat mirrors, the position of which can be adjusted to in effect create a surface with any desired curvature. Even if Archimedes had been able to construct such a mirror, he would have had no way to calculate the radiant flux at a given distance from the mirror; the concepts necessary for such a calculation did not exist. The fact remains that smaller burning mirrors were well known at the time. At best, however, evidence that Archimedes had enough information to make the weapon work is inconclusive.

Simms next investigated how effective a properly designed large burning mirror would have been in battle by examining the conditions under which concentrated sunlight will ignite wood and start a continuing fire. (The sails of the ships would not have been a target because they were furled when the ships were attacking or at anchor.) Under the most favorable conditions a stationary block of wood at the exact focus of a long-focal-length mirror takes at least 30 seconds to ignite. In other words, it is difficult to see how a burning mirror could have been kept focused on the damp material of a ship long enough to set it afire. A much more efficient procedure would have been to hurl pots of flammable material onto the deck.

"Thus there are ample historical, scientific and military grounds for concluding that Archimedes did not use a burning mirror as a weapon of war," Simms writes. "As a weapon of war the burning mirror was of little value, and the probability of being able to use it was far too low for any mathematician to risk."

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BOK GLOBULE known as Barnard 335 forms an apparent hole in the sky in this photograph made by Bart J. Bok with the 90-inch reflecting telescope of the Steward Observatory of the University of Arizona. Such objects, first recognized as a class by Bok, are isolated, compact, geometrically regular interstellar clouds of dust and gas. "Barnard" refers to Edward Emerson Barnard, who made extensive photographic surveys of dark interstellar clouds in the early part of the century. Bok globules are not uniformly opaque. They usually thin out away from a dense core, so that stars can shine through their outer regions. Barnard 335 is some 1,200 light-years away from the solar system and is about two light-years in diameter. The mass of gas in it is estimated to be more than 25 times the mass of the sun.

Bok Globules

They are spherical clouds of interstellar dust and gas that show up against a background of stars or of luminous gas. The evidence suggests that they are collapsing and may be stars in the making

by Robert L. Dickman

The expression "interstellar space" evokes a vast emptiness. Indeed, the stars of our galaxy are separated by distances almost impossible to comprehend on the level of everyday experience. For example, in the vicinity of the sun the mean distance between neighboring stars is some three light-years, or about 17 trillion miles. Moreover, the space between the stars is a vacuum exceeding any achieved on the earth. It is, however, a lumpy kind of vacuum. Scattered among the stars of our galaxy are huge, mostly nonluminous clouds of thin, dusty gas. Although such clouds make up less than 10 percent of the total mass of the galaxy, they are a dynamic and important component of it, not least because they are the raw material out of which new stars are made. By studying the interplay of physical processes observed in interstellar clouds astronomers hope to better understand the sequence of events that ultimately gives rise to stars. More broadly, they hope to clarify the basic physical mechanisms that govern the behavior, composition and evolution of the interstellar medium.

This discussion will focus on a class of interstellar clouds known as Bok globules. Such objects can be defined as interstellar dust clouds that are compact, fairly opaque, isolated and regular in form. They are named after Bart J. Bok, the Dutch-American astronomer who more than 30 years ago drew attention to them as a distinct class of interstellar clouds and who suggested their possible status as the precursors of stars. Although the present evidence tends to confirm the correctness of Bok's original and in some ways daring conjecture, it has become clear over the past few years that the most conspicuous sites of star formation are not globules but the massive molecular clouds associated with the bright clouds of diffuse ionized gas known as H II regions. Thus astronomical interest in Bok globules as sites of star birth has somewhat declined. The globules are increasingly recognized, however, as an important source of information about the more highly condensed states of the interstellar medium.

Bok globules are the smallest and most regular structures known in the interstellar medium. Their apparent lack of a strong internal energy source, such as a recently formed cluster of hot young stars, greatly limits the range of physical processes the astrophysicist needs to consider in trying to understand them. Lacking an internal energy source, Bok globules are among the coldest objects in interstellar space: most are only about 10 degrees Kelvin (10 degrees Celsius above absolute zero). Hence they are nearly ideal subjects for comparison with theoretical cloud models, the highly simplified representations of essential cloud physics that astrophysicists construct to test their understanding of interstellar processes.

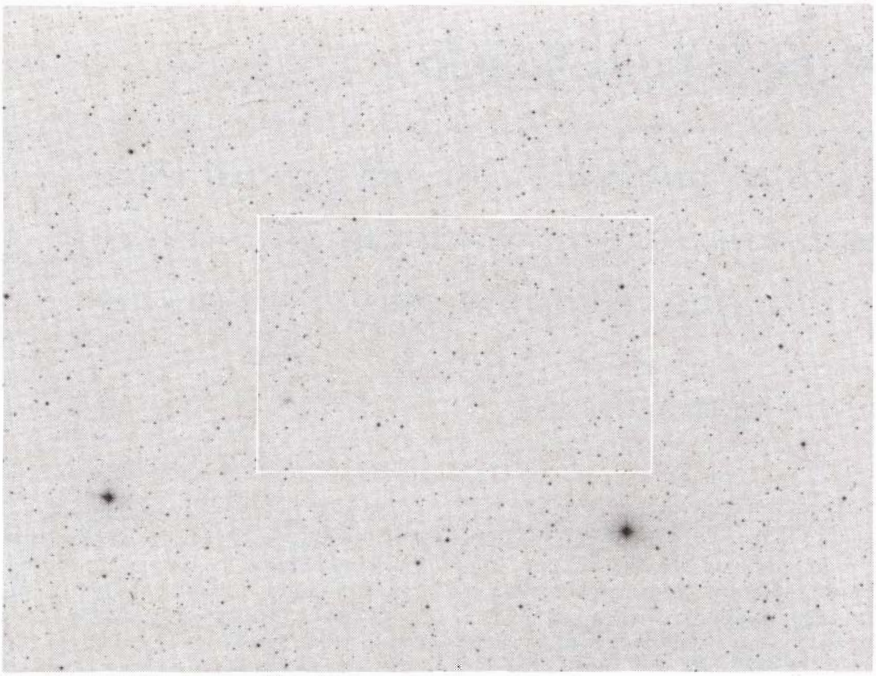
Let me begin by placing the Bok globules against the large-scale backdrop of our galaxy, the aggregation of some 100 billion stars that includes the sun as a minor member. The forces of self-gravitation and rotation have confined the bulk of the stars in the galaxy to a flattened spiral disk roughly 100,000 light-years across. Except for a bulge at the center the disk is only 600 to 1,200 light-years thick. The solar system lies in the galactic disk about two-thirds of the way out from the center, so that we perceive the disk from the inside as the Milky Way, the luminous band in the night sky produced by the light of millions of stars too faint to resolve with the unaided eye.

Since the interstellar medium has mass, it is subject to the same forces of gravity and rotation that have shaped the galaxy. It is therefore hardly surprising that the interstellar clouds are also largely confined to the galactic disk. The clouds consist mainly of hydrogen, but they also contain a small admixture of tiny solid particles: the interstellar dust. This comparatively insignificant trace of dust, which represents less than 1 percent of the total mass of the interstellar clouds, dims and reddens starlight passing through the clouds in much the same way that dust in the earth's atmosphere dims and reddens the light of the setting sun. If a cloud is dense enough, it will totally block the passage of starlight and create what seems to be a hole in an otherwise rich field of stars.

The Detection of Dark Clouds

For a dark interstellar cloud to be detected by optical methods three conditions must normally be satisfied. First, the cloud must contain enough dust along the line of sight to noticeably diminish the number of stars seen through it. Second, since the reduction in the number of stars seen through the cloud can be judged only in relation to the background density of stars in regions immediately adjacent to it, the cloud must be in a part of the sky where the number of stars per unit area is large. In general the smaller and less absorptive the cloud one hopes to detect is, the richer the stellar background must be in order for one to be confident that the diminution in star numbers is caused by dust absorption and not merely by a statistical fluctuation in the stellar background. Third, the cloud must be fairly close to the solar system (for practical purposes within about 3,000 light-years); otherwise there may be too many stars lying in front of the cloud for its detection to be certain.

The optical detection and study of small interstellar dark clouds therefore calls for long-exposure photography with large telescopes. Only such an approach is capable of bringing out the large number of faint stars that are a prerequisite for detection. This restriction applies to most interstellar dark clouds but not to all. A few complexes of interstellar gas and dust are so large and so opaque that they can easily be seen with the unaided eye. Indeed, they were surely apparent to ancient astronomers, although their true nature could hardly have been appreciated. The most prominent opaque complex for those who live in the Northern Hemisphere is



DIFFICULTY OF IDENTIFYING DARK INTERSTELLAR CLOUDS is demonstrated in this photograph, reproduced from a negative print, of a region in the constellation Ursa Major. Since the region is remote from the central plane of our galaxy, the density of stars is low. Beverly T. Lynds of the Kitt Peak National Observatory has called attention to the star-poor region within the white rectangle and has raised the question of whether the region represents a dust cloud or merely a statistical fluctuation in the stellar background. She has concluded that the presence of a cloud is highly unlikely. The conclusion is supported by the absence of detectable radio emission from carbon monoxide molecules, which are invariably associated with clouds of dust and gas. Photograph, which was made with 48-inch Schmidt telescope on Palomar Mountain, is copyrighted by National Geographic–Palomar Observatory Sky Survey.

the Great Rift in Cygnus, a chainlike complex of dark clouds that more or less continuously obscures a narrow band of the Milky Way as it runs through the constellations Cygnus and Aquila.

Even though these densest and darkest states of interstellar matter were probably the first known manifestations of the interstellar medium, they have been slow to receive detailed scientific examination. Even with the rapid advances in photographic astronomy being made in the late 19th and early 20th centuries there was for many years a vigorous debate over the nature of the "holes in the heavens" graphically revealed by long-exposure photography. Although some astronomers readily accepted the reality of obscuring clouds of interstellar matter, others steadfastly maintained that the "holes" were precisely that, empty spaces somehow torn in the stellar background. The intensity of the debate early in this century is vividly apparent in the writings of the American astronomer Edward Emerson Barnard. With his German contemporary Maxmilian Wolf, Barnard shares the principal honor of founding the photographic study of dark interstellar clouds as a branch of observational astronomy. Although he was early convinced of the reality of the structures he had carefully photographed and studied, there is an undercurrent of caution in his many publications on the subject. He did not explicitly commit himself (in print) to the reality of his "dark markings" until 1919.

The notion of actual holes torn in the stellar background by mysterious forces was gradually laid to rest early in this century as it became clear that the sharp boundaries of many dark clouds would be quickly obliterated by random stellar motions if they were truly empty spaces. Simultaneously the concept of a widespread, largely nonluminous, dust-bearing interstellar medium was rapidly gaining currency. The existence of absorptive interstellar matter had been suggested as far back as early in the 19th century by the Russian astronomer Friedrich G. W. Struve. The idea was decisively confirmed in the late 1920's by the work of the American astronomer Robert J. Trumpler. The resulting picture of a ubiquitous and largely diffuse distribution of obscuring matter in the galaxy explained much, including the progressive dimming and reddening of stars and star clusters with increasing distance from the earth and the apparent concentration of other galaxies in regions of the sky away from the plane of the galaxy (since most of the dust lies close to the plane of the galactic disk). The character of dark clouds as unusually dense and well-localized objects embedded in a more diffuse interstellar medium was also becoming clear.

Cold interstellar gas has few observational "signatures" in the optical region of the spectrum, but early in this century indirect evidence had gradually accumulated to suggest that significant amounts of gas are intermixed with the interstellar dust. Bright nebulas were known to be composed of gases such as hydrogen, helium, carbon, oxygen and nitrogen. In addition spectral absorption lines due to calcium and sodium atoms lying along the line of sight to certain distant stars had been discovered. Thus by the time Trumpler had established the presence of interstellar dust the existence of interstellar gas was already firmly accepted, although its precise relation to the dust, particularly in dark clouds, was not well understood. The study of the gas component of the interstellar medium expanded rapidly in the early 1950's, when it became feasible to construct sensitive radio receivers capable of detecting the characteristic 21-centimeter emission line of atomic hydrogen.

This spectral line is produced when the spin axis of the hydrogen atom's single electron flips 180 degrees with respect to the spin axis of the atom's nucleus (a proton) and emits a photon with a wavelength of 21 centimeters. In 1945 H. C. van de Hulst of the University of Leiden had predicted that since hydrogen is the most abundant element in the universe, widespread 21-centimeter emission might be observable with radio telescopes equipped with sensitive receivers. His hypothesis was strikingly confirmed six years later, when Harold I. Ewen and Edward M. Purcell of Harvard University first detected interstellar emission from atomic hydrogen.

The Molecular Approach

With that profound discovery investigations of the two components of the interstellar medium, the gas and dust, rapidly began to merge. In 1955 A. E. Lilley of Harvard produced a definitive study of the quantitative relation between the two components. By surveying large and comparatively diffuse areas of dust obscuration (very dark clouds were generally excluded) he showed that along any given line of sight in the galaxy the ratio of the abundance of atomic hydrogen to that of dust was remarkably constant. Surprisingly, however, when efforts were made to exploit the 21-centimeter line as a probe of the darkest parts of the interstellar medium, very little atomic hydrogen could be detected.

Accurate estimates of the dust content of dark clouds could be made, partly as a result of refinements in statistical star-counting techniques worked out by Bok in the 1930's. If "Lilley's law" applied to dark clouds, radio receivers of only modest sensitivity should have easily detected the accompanying hydrogen. Yet beginning with a study made by Bok and his co-workers at Harvard in 1955 it was realized that in dark nebulas the abundance correlation between dust and atomic hydrogen either failed or was weakly negative. Hence the prospect of having a direct probe of the interior of dark nebulas seemed to collapse.

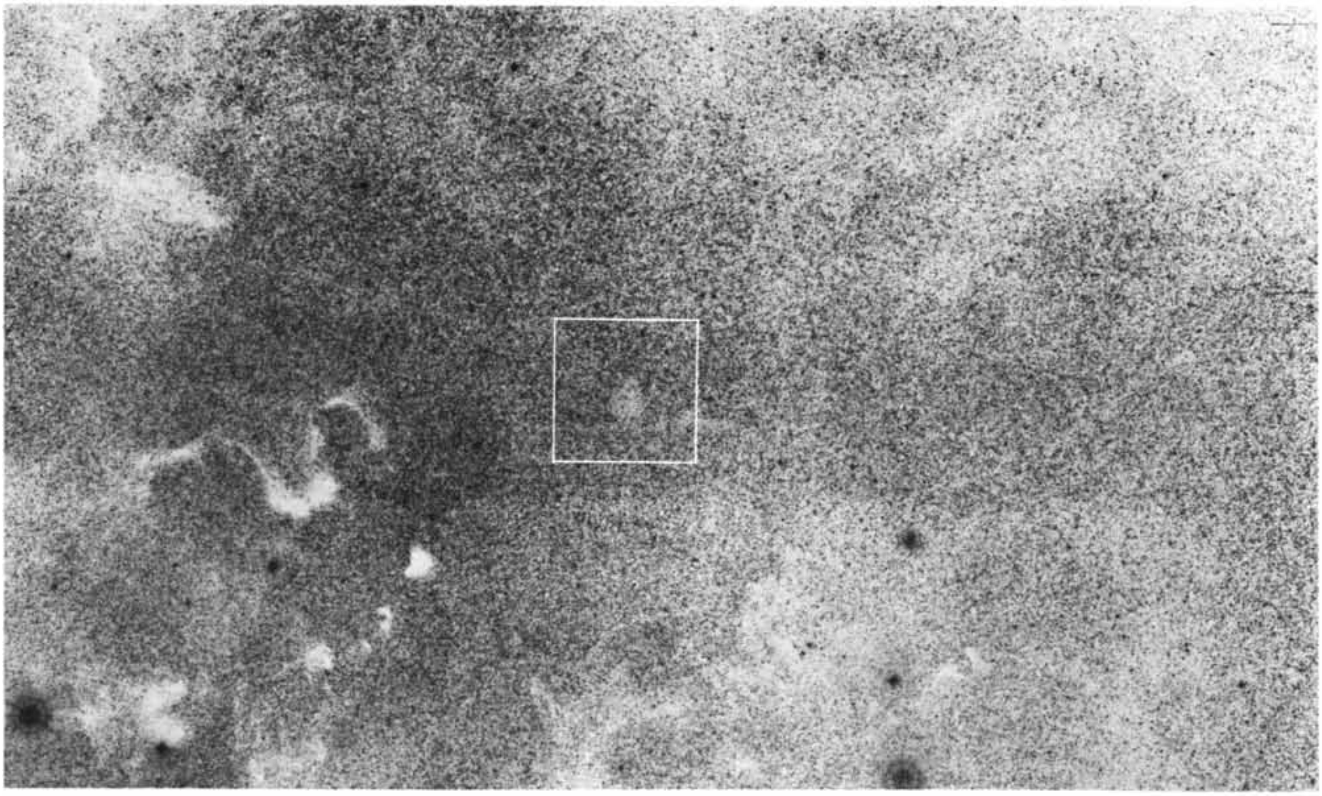
How was the failure of the correlation to be explained? The answer, which did not fully emerge until late in the 1960's, is that the hydrogen is there but in molecular rather than atomic form. The hydrogen molecule, H_2, has no prominent spectral signature analogous to the 21-centimeter line that is capable of penetrating the earth's atmosphere, and so its presence or absence has been nearly impossible to establish. Moreover, it was soon realized that in any dark cloud of more than modest opacity the hydrogen atoms must rapidly coalesce into molecules.

There are essentially two reasons why. One reason has to do with the fact that left unshielded in interstellar space a hydrogen molecule is quickly dissociated into two hydrogen atoms by the ultraviolet radiation that permeates the galaxy. The dust within a dark cloud, however, tends to screen out the disruptive radiation. Even more important, molecular hydrogen is itself quite opaque to ultraviolet radiation. Therefore when a small amount of it forms in a dark cloud, the interior of the cloud is well shielded against ultraviolet photons. The other reason is that the formation of the hydrogen molecules is promoted by the dust itself. Molecules of hydrogen are not simply formed by the collision of two hydrogen atoms. A third body, such as a grain of dust, is needed as a formation site. Hydrogen atoms occasionally stick to dust grains after collision and are able to move around on the grain surface. When two atoms on the grain surface come together, they release energy that is taken up by the grain. The hydrogen molecule thus created can be ejected from the grain surface by thermal evaporation.

If hydrogen in the darkest clouds is virtually all in molecular form, how can conditions in the interior of such clouds be investigated? Moreover, since only nearby dark clouds can be identified by optical techniques, how can the distribution of dark clouds in the galaxy as a whole be studied? There is a solution to such problems. Dark clouds contain traces of molecules other than H_2 that have spectral lines detectable by modern radio-telescope receivers. The new specialty of molecular astrophysics has provided the key needed to unlock the interior of dark clouds and also to reveal their large-scale distribution.

It is now apparent that the same conditions giving rise to the conversion of hydrogen atoms into molecules also favor the production of other molecules: carbon monoxide (CO), formaldehyde (H_2CO), carbon monosulfide (CS), hydrogen cyanide (HCN) and considerably more complex molecular species. So far more than 30 different molecules have been detected in the denser parts of the interstellar medium. The majority of them are confined to clouds of exceedingly high density and are not observed in Bok globules. Carbon monoxide, the commonest molecule after H_2, is less abundant than H_2 by a factor of about 10,000. In spite of the great scarcity of carbon monoxide and the other less abundant molecules, they serve well as the radio probes needed for the systematic study of dark clouds.

This, then, is the picture of the interstellar medium as we now perceive it. A small fraction of the medium exists in the form of luminous, largely ionized and tenuous gas: the H II regions, produced by the proximity of the gas to hot young stars with a copious output of ultraviolet radiation. The rest of the interstellar medium is about equally divided between clouds in which the gas is mostly un-ionized atomic hydrogen and denser, more opaque clouds in which the gas is mostly molecular hydrogen. The more opaque clouds can be divided into



DIFFUSE BOK GLOBULE Barnard 255 lies within the white rectangle in this negative print. Although the cloud contains less dust and gas than most Bok globules do, it stands out rather clearly because it is in a star-rich region. If Barnard 255 happened to lie in the region of the sky shown in the illustration on the opposite page, it would be nearly impossible to detect visually. It could be detected, however, by the weak radio emission from carbon monoxide, provided, of course, one knew where to look in the first place. This photograph was also made with the 48-inch Schmidt telescope and is copyrighted by National Geographic–Palomar Observatory Sky Survey.

two convenient but somewhat arbitrary types, confusingly termed molecular clouds and dark clouds. Both types of clouds are dense and dark, but molecular clouds are distinguished by their large size (some are tens of light-years across), high central density and large mass (some have a mass many thousand times greater than that of the sun). Molecular clouds are nearly always associated with H II regions, and they take their name from the rich array of molecular species that can be detected in them. Dark clouds are generally smaller, less dense, less massive and are usually not associated with bright emission nebulosity. In general dark clouds exhibit a wide variety of shapes: chainlike, ribbonlike, crenelated and so on. It is within this diverse group of objects that the Bok globules find their niche.

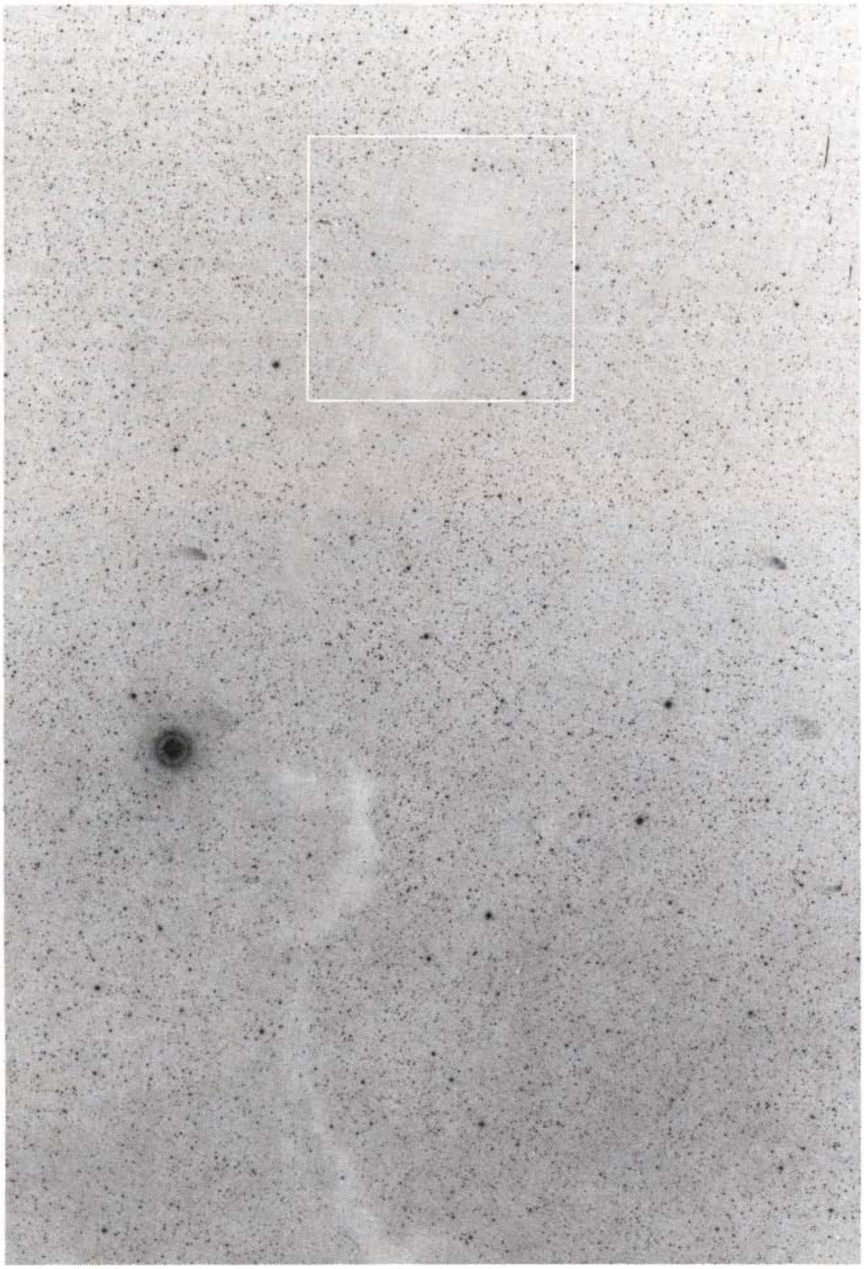
Defining a Globule

What justifies singling out the Bok globules as a distinct class of dark clouds? When Bok and E. F. Reilly first called attention to the globules in 1947, they were seeking clouds that might be identified with the earliest stages of star formation. Their search was guided by two principal criteria. First, they looked for regions of substantial optical opacity, produced by a concentration of dust and gas within a fairly small volume. Second, they looked for regions that were apparently round enough to suggest that the forces of self-gravitation had begun to operate as a prelude to the collapse of the cloud and the ultimate formation of stars.

Bok and Reilly identified two types of interstellar dark clouds that seemed to satisfy the two criteria. The first and more readily studied group consists of what are sometimes called larger Bok globules. They are highly opaque and roundish isolated dark clouds, many examples of which can be found in Barnard's classic photographic atlas of "dark markings." The second group, about which little is yet known (in part because the clouds are too small to be studied effectively with present-day radio telescopes), consists of minuscule, extremely opaque condensations seen projected against certain H II regions. Their relation to their larger counterparts remains obscure, but it now seems clear that the two types of objects differ in more than size.

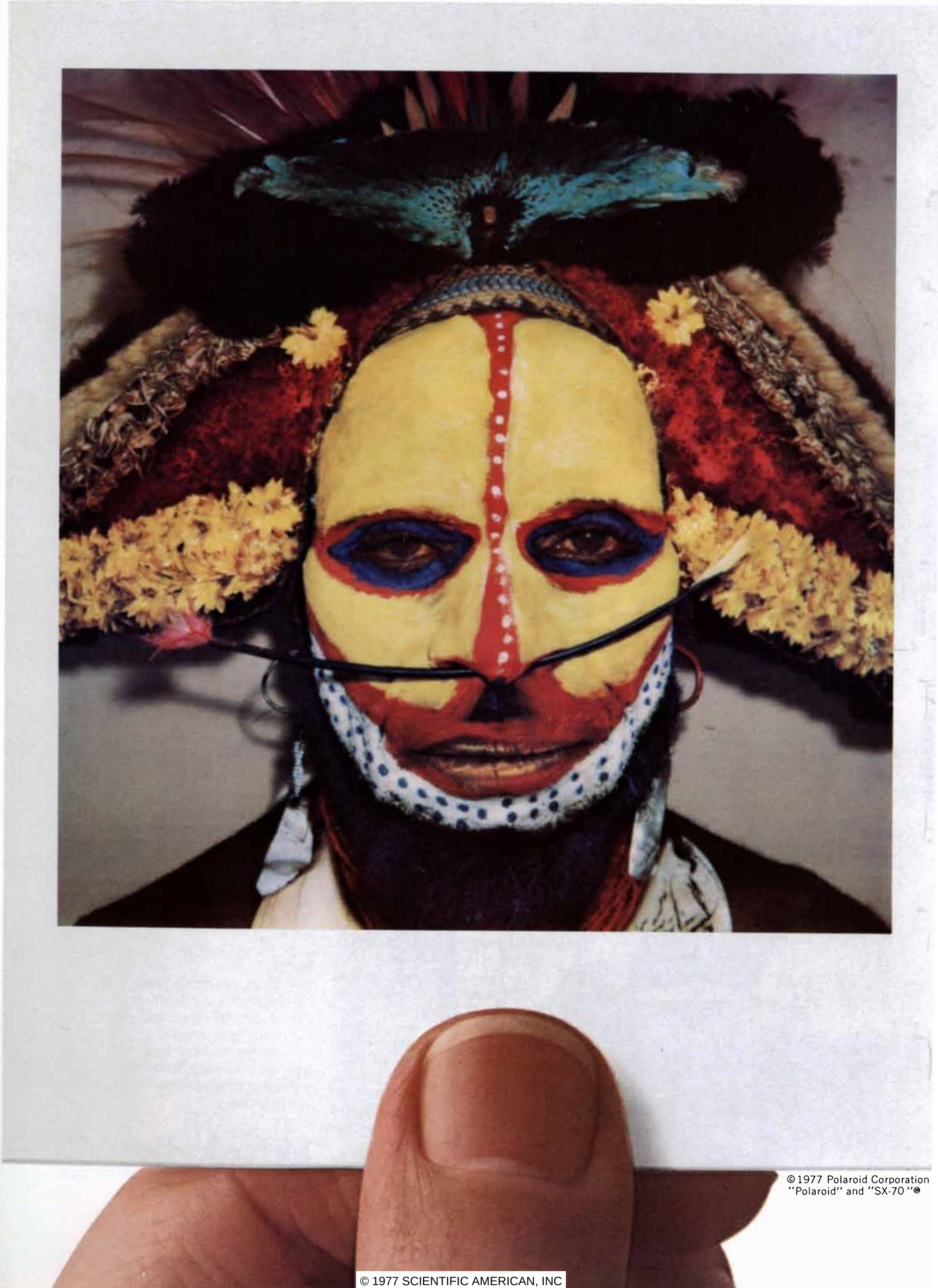
Just because the small globules are seen projected against H II regions does not prove that the two are physically associated; all one can say for sure is that the globules lie somewhere between the H II regions and our telescopes. The assumption persists, however, that these small clouds of gas and dust, often only a few tenths of a light-year across, actually lie close to the ionized regions seen behind them. Recently George H. Herbig of the University of California at Santa Cruz has pointed out that the small globules are actually not very spherical. High-resolution photographs disclose that the clouds often have a marked and systematic elongation, which strongly suggests they are being distorted and torn apart by the hot H II regions in which they are apparently embedded.

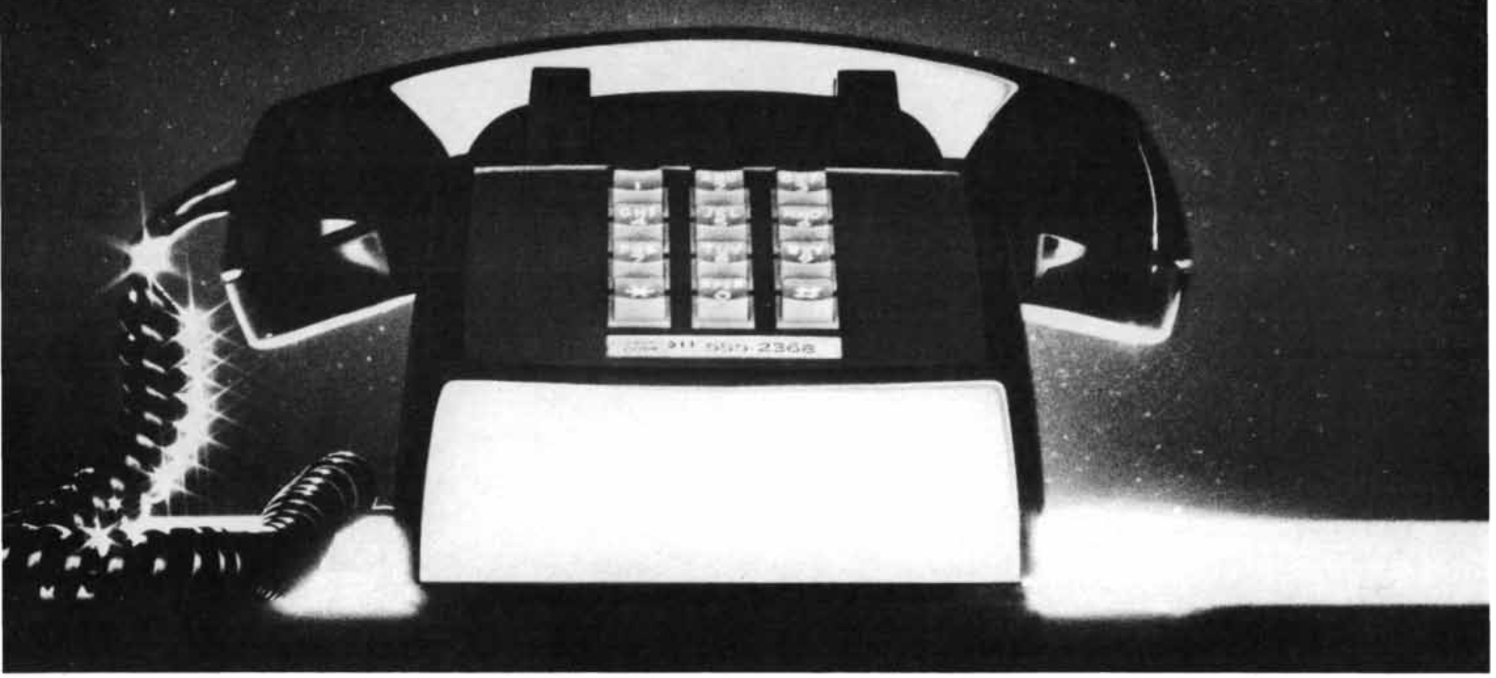
As for the larger Bok globules, one cannot be dogmatic in describing them as a distinct class of dark clouds. Form is necessarily a fuzzy criterion when it is applied to the interstellar medium, and no interstellar cloud can be said to be perfectly round in appearance. Moreover, many structures that seem on casual inspection of a photographic plate to be highly symmetrical often reveal a substantial lack of circular symmetry when a detailed quantitative study of their dust distribution is made. Nevertheless, retaining the Bok globules as a distinct category of interstellar clouds remains highly useful if it is understood that the globules broadly encompass all isolated, compact interstellar dark clouds that exhibit a modicum of geometric regularity. Such clouds can be



COMPLEX OF DARK CLOUDS appears in this negative print of a region in Scorpius. Although the picture was made in the red part of the spectrum, which maximizes penetration of dust, cloud structures stand out clearly. The two globules within the rectangle appear to have been pinched off from the elongated dust cloud. This photograph was also made with 48-inch Schmidt and is copyrighted by the National Geographic–Palomar Observatory Sky Survey.

Enlarged reproduction of an SX-70 print: Huli tribesman from the Southern Highlands of Papua, New Guinea.





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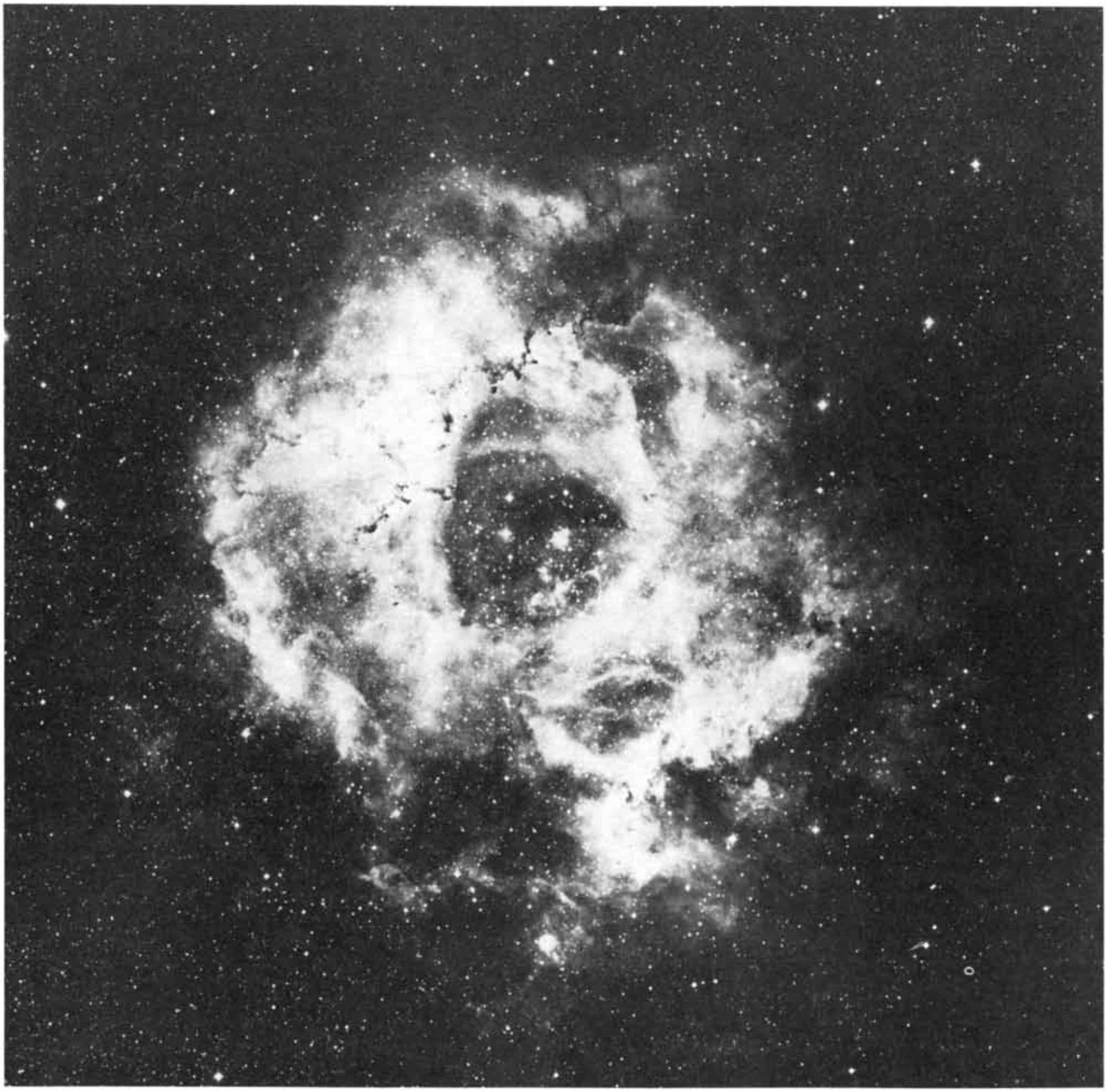
regarded as unit structures in the interstellar medium.

Gravitational Collapse

How does one begin to assess Bok's conjecture that the globules are gravitationally unstable objects that will ultimately contract to form one or more stars? Given the present absence of firm observational evidence that stars are currently being born within globules one must proceed by evaluating the physical requirements for collapse. At first the requirements appear to be conceptually simple. Suppose one knows the mass, radius and internal temperature of a globule, which as a first approximation can be assumed to be perfectly uniform and spherical. In this picture the self-gravitation of the cloud, which tends to compress it, depends only on the mass and radius of the cloud. The tendency toward collapse is resisted by the internal pressure of the gas in the cloud, which is produced by the nonzero internal temperature of the globule.

Suppose now one imagines the mass and temperature of the cloud to be fixed and considers a succession of possible values for the radius of the cloud. Clearly the larger the radius is, the weaker the gravitational attraction is that the constituents of the cloud exert on one another; the force of gravity between any two masses decreases as the inverse square of their separation. As the radius of the globule is made smaller, however, a critical value is reached below which gravitational attraction overpowers pressure, and the predominant internal motion of the cloud becomes collapse.

To apply this simple picture to a real Bok globule therefore requires knowing



MINUSCULE BOK GLOBULES resembling small black dots are sharply etched against the brilliant background of the Rosette Nebula in this photograph made with the 200-inch telescope on Palomar Mountain. Because the tiny globules seem to be associated with the hot, ionized gas of the nebula, they may not be strictly comparable to the larger Bok globules and may be in the process of disruption.

three characteristics of the cloud: its radius, its mass and its temperature. If they are known, one can readily compute whether or not the radius of the globule is below the critical value required for collapse. One can determine the radius of a globule by measuring its apparent size on photographic plates and then computing the actual radius from estimates of the cloud's distance. Distance estimates for dark clouds, however, are usually uncertain by about a factor of two, which implies that there is a corresponding uncertainty in estimates of radii.

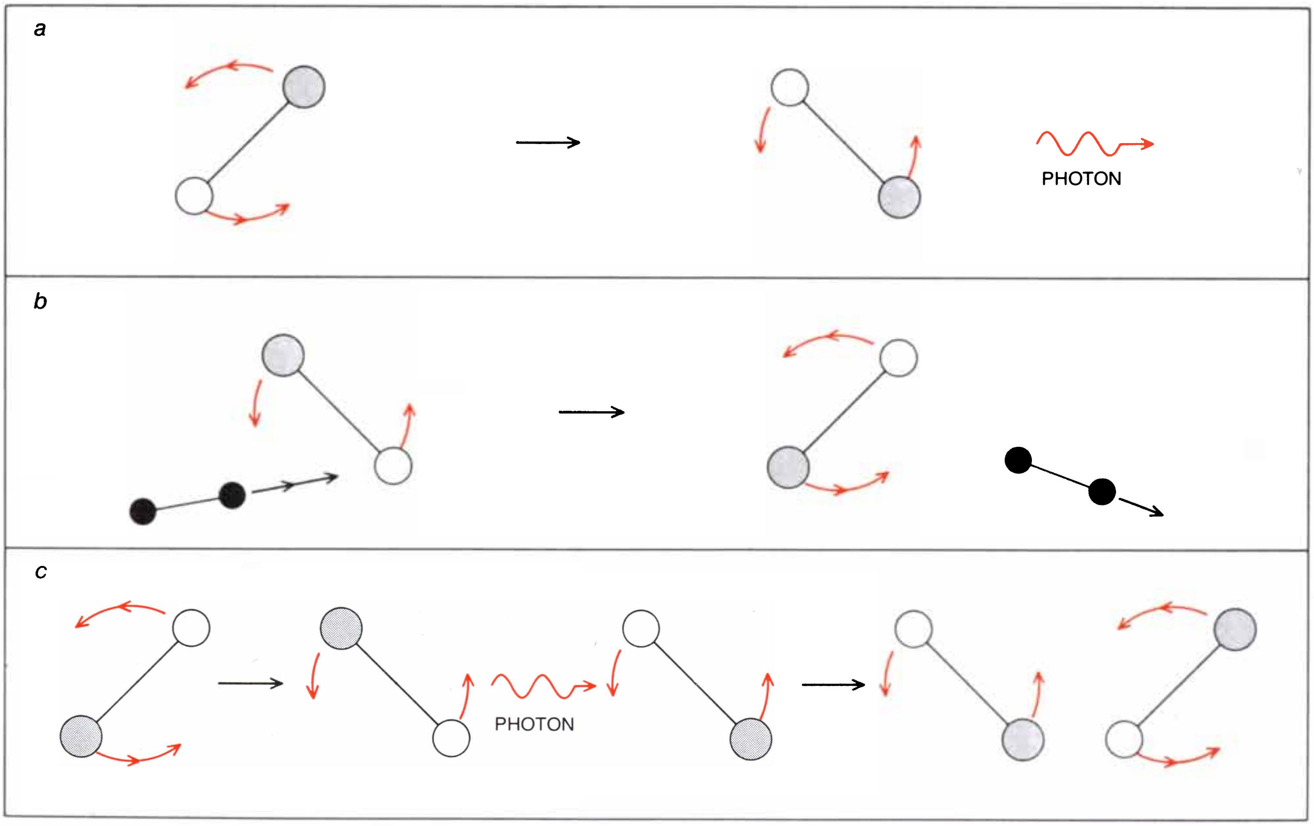
Mass too can be obtained from photographic plates, again with an attendant margin of uncertainty. The typical method is to use the statistics of star counts to estimate the amount of dust obscuration produced by the cloud. This yields an estimate for the total mass of dust. One can then estimate the mass of hydrogen in the cloud by means of Lilley's hydrogen-to-dust ratio. As I have mentioned, the ratio appears to break down at the very high densities that exist within massive molecular clouds. For the gas and dust densities typical of Bok globules, however, Lilley's ratio seems reasonably secure. In any case the mass derived in this way will usually be a lower limit, since many globules have a totally opaque core whose dust content can be assigned only a minimum value. Thus within reasonable limits one can obtain the radii and the minimum masses of globules.

The next problem is to estimate the cloud's internal temperature. It is here that the value of molecular-line radio astronomy becomes evident. Although there are several essentially independent methods of employing molecular observations to determine the gas temperature within a dark cloud, perhaps the most powerful procedure involves observations of the carbon monoxide molecule.

As we have seen, carbon monoxide is the most widespread trace molecule in the interstellar medium. Its spectral line at a wavelength of 2.6 millimeters becomes readily observable under about the same conditions that favor the conversion of atomic hydrogen into molecular hydrogen. The processes that give rise to the carbon monoxide emission line are essentially simple and apply equally well to a number of other astrophysically important molecules. The carbon monoxide molecule can be visualized as a dumbbell-shaped structure with a carbon atom at one end and an oxygen atom at the other. It is capable of rotating end over end around its center of mass. The rotation speeds of the molecule are not arbitrary, however. Quantum-mechanical principles dictate that only certain discrete values of rotational angular momentum are allowed. The larger the angular momentum of the molecule is, the larger is the energy of rotation.

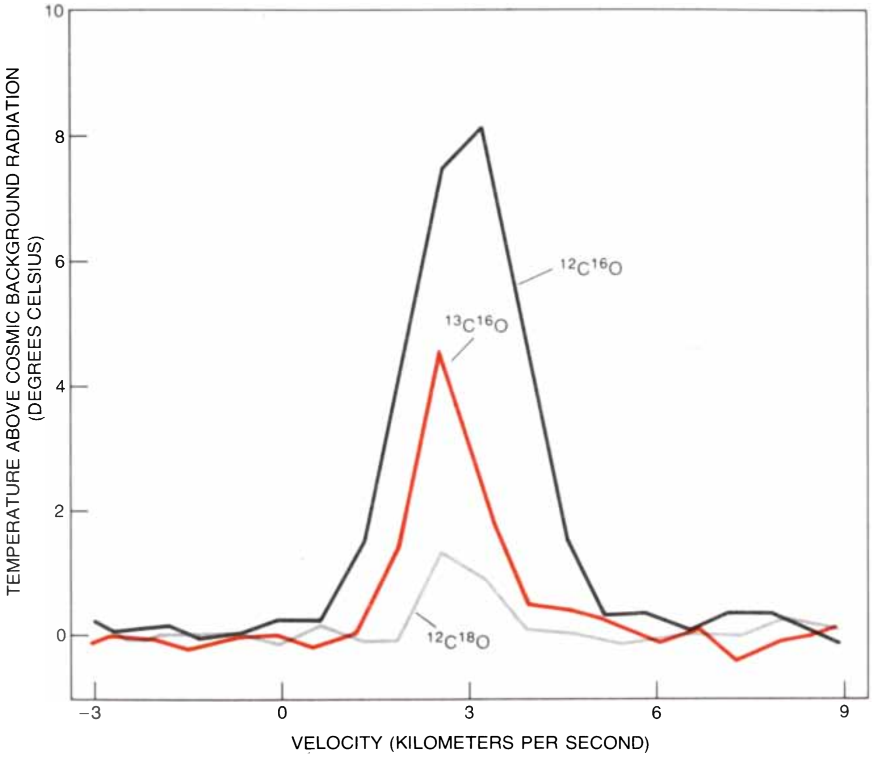
An isolated carbon monoxide molecule in any rotational state except the ground state (the state of no rotation) will spontaneously and abruptly decrease its angular momentum by a succession of quanta, or discrete units, until it reaches the ground state. With each stepwise transition between adjacent energy levels the molecule emits a photon whose wavelength is inversely proportional to its energy, thereby discharging the quantum of energy separating the two rotational states. For present-day radio astronomy the most important transition in carbon monoxide is the one connecting the first allowed rotation state with the ground state, which occurs with the emission of a photon whose wavelength is 2.6 millimeters.

Molecules in all states except the ground state will rapidly emit photons and decay to the ground state. How,



MOLECULAR COLLISIONS AND EMISSIONS effect the excitation of carbon monoxide in Bok globules and other dark clouds. Carbon monoxide molecules, represented by gray and white spheres, have angular momenta, or rotational energies (*curved arrows*), that vary in quantum steps. When the molecule drops from one rotational state to the next state, the energy difference appears in the form of a photon. A carbon monoxide molecule can reacquire energy by collision with a hydrogen molecule (*two black spheres*), which loses translational energy (*b*). In some cases (*c*) the photon emitted by one carbon monoxide is reabsorbed by another carbon monoxide before the photon can escape from the cloud. The process, called radiative trapping, can help to maintain distribution of excited states in gas clouds.

then, is it possible for interstellar clouds to emit 2.6-millimeter and other spectral-line photons indefinitely? The main explanation is that thermal collisions between the abundant hydrogen molecules and molecules of the trace chemical species continuously maintain a certain fraction of carbon monoxide and other molecules in elevated energy states. In addition before some of the photons emitted by carbon monoxide and the still scarcer molecules can escape from the cloud they are often reabsorbed by molecules of the emitting species that happen to lie in lower energy states. This process, known as radiative trapping, can help to maintain a significant steady-state population of excited molecules. Ultimately a balance may be reached among all the processes of excitation and radiative decay to maintain a steady-state distribution of the various molecular species at various energy levels. If such a steady state is reached, the molecular excitation is said to be thermalized and accurately reflects the temperature of the molecular hydrogen in the cloud.



EMISSION FROM ISOTOPIC FORMS OF CARBON MONOXIDE provides clues to the density and motion of the gas in an interstellar cloud. The curves show the intensity of spectral lines from one location in the Bok globule Lynds 134. The intensity is expressed in degrees Celsius above the absolute temperature of the cosmic background radiation, which is about three degrees Kelvin. The strongest emission is from the most abundant form of carbon monoxide, $^{12}C^{16}O$, which consists of carbon of atomic weight 12 and oxygen of atomic weight 16. The next-strongest emission is from carbon monoxide containing carbon 13, $^{13}C^{16}O$. The weakest emission is from the form containing oxygen 18, $^{12}C^{18}O$. The spectra enable one to calculate approximate number of molecules of each type along line of sight. Width of the spectral lines indicates the velocity distribution of molecules. Plus values mean gas is moving away from observer. Spectra were obtained by W. L. H. Shuter, W. H. McCutcheon and M. J. Mahoney of University of British Columbia with 4.6-meter radio telescope of Aerospace Corporation.

Probing a Globule

Suppose, then, one observes a particular molecular transition, such as the 2.6-millimeter line of carbon monoxide, which arises from two rotational levels whose steady-state populations are thermalized. One can then determine the peak gas temperature within the emitting cloud directly from the intensity of the spectral line, provided that enough molecules along the line of sight are contributing to the observed emission. To meet this requirement the spectral line under observation must be "optically thick." It turns out that the 2.6-millimeter line of carbon monoxide in dark clouds does arise from two rotational levels of the molecule whose populations are usually thermalized, or very nearly so, partly because the comparatively large abundance of carbon monoxide allows radiative trapping to contribute strongly to the excitation of the molecule. Moreover, a simple test is available to determine whether or not a given carbon monoxide line is optically thick.

The commonest isotopic combination of carbon monoxide in interstellar clouds is one in which the carbon nucleus consists of six protons and six neutrons (carbon 12) and the oxygen nucleus consists of eight protons and eight neutrons (oxygen 16). This form of the molecule is denoted $^{12}C^{16}O$. Also present, although less abundant by a factor of at least 50, are molecules with a carbon-13 nucleus: $^{13}C^{16}O$. Because of the larger mass of $^{13}C^{16}O$ the energies of its rotational states lie about 5 percent lower than the corresponding states of $^{12}C^{16}O$. Thus if a radio astronomer seeks to determine whether or not a given $^{12}C^{16}O$ spectral line is optically thick, he need only retune his receiver to a slightly lower frequency and attempt to detect a corresponding $^{13}C^{16}O$ line from the same location in the cloud. If strong emission from the rarer isotopic species is found, it is then certain that the $^{12}C^{16}O$ line is optically thick and is a valid index of the temperature of the cloud.

I have recently employed such methods to investigate a sample of eight Bok globules. They range in mass from about 19 to more than 740 times the mass of the sun and in radius from about one light-year to 3.8 light-years. With the exception of Barnard 5, all have an internal temperature of about 10 degrees K., which is typical of interstellar dark clouds. Can one draw any conclusions about their gravitational stability? If one simply compares the observed radii of the globules with the calculated critical radii below which, for a given temperature and mass, they should collapse, one finds that all eight have radii well below the critical value. Hence if radius, mass and temperature were the sole controlling parameters, one would have to conclude that these eight Bok globules are all in a vigorous state of collapse.

One must, however, look into matters somewhat more deeply. We have implicitly assumed that the only force capable of opposing self-gravitation in the clouds is thermal pressure. Thus we have ignored at least three additional retarding agents: rotation, magnetic fields and hydrodynamic turbulence. Each alone, or two or more in combination, could prevent the collapse of a cloud even though its observed radius is much smaller than what we have been calling the critical value.

Let us first consider the possible effect of rotation in preventing the collapse of a globule. Clearly if a cloud is spinning around its center of mass, centrifugal forces could retard or completely suppress its further coalescence. Among other things, however, the observed geometry of the globules suggests that substantial rotational velocities must be absent; otherwise the clouds would become flattened and would therefore tend to appear more or less lens-shaped unless we happened to be viewing them along their axis of rotation. This essentially qualitative argument is strongly

BOK GLOBULE NAME	APPROXIMATE RADIUS (LIGHT-YEARS)	APPROXIMATE MINIMUM MASS (SOLAR MASSES)	APPROXIMATE TEMPERATURE (DEGREES KELVIN)	APPROXIMATE CRITICAL RADIUS (LIGHT-YEARS)	APPROXIMATE CRITICAL ROTATION SPEED (KILOMETERS PER SECOND)
BARNARD 5	3.8	740	17	212	5.7
BARNARD 92	1.0	24	9	13	2.0
BARNARD 133	1.9	60	10	29	2.3
BARNARD 134	1.6	19	9	10	1.4
BARNARD 335	1.0	23	9	12	2.0
BARNARD 362	1.3	33	11	15	2.1
LYNDS 134	2.1	66	13	25	1.6
LYNDS 1262	1.6	63	11	15	2.6

SAMPLE OF EIGHT BOK GLOBULES investigated by the author shows a considerable variation in size and mass but only a narrow variation in temperature. The critical radius is the radius below which a spherical globule of the indicated mass must collapse by self-gravitation if the only countervailing force is the thermal motion of gas at the measured temperature. The last column shows the minimum critical speed of rotation that would have to be added to the thermal motion in order to prevent the gravitational collapse of each globule.

supported by evidence from molecular radio astronomy.

Let us assume we are observing a rotating cloud whose axis of rotation is not perpendicular to the line of sight. Because of the Doppler effect photons emitted by molecules in the edge of the cloud coming toward us will be blue-shifted, or increased in frequency, by an amount proportional to the rotation speed at that edge. Conversely, photons emitted by molecules in the opposite edge of the cloud, which is moving away from us, will be red-shifted, or decreased in frequency, by the same amount. Therefore if we map the emission across the face of a rotating cloud, we will observe a systematic displacement in the apparent frequency of the emitted lines; the total shift will be twice the shift at one edge of the cloud.

Such rotation effects would be immediately apparent if they were of the magnitude required to prohibit the collapse of a cloud. For the eight Bok globules in my sample, however, the systematic velocity shifts that might be attributed to rotation amount to less than about .7 kilometer per second, or between half and an eighth the values needed to offset gravitational collapse. Therefore unless all the clouds in the sample happen to have their rotation axis tilted by more than about 70 degrees from the perpendicular to the line of sight, which is extremely unlikely, rotation sufficient to prevent collapse does not seem to be present.

Magnetic Fields

It is less easy to rule out the other two potential retarding forces: magnetic fields and turbulence. The collapse-inhibiting effect of a magnetic field can be readily appreciated. If one tries to push like poles of two magnets together, their fields strongly resist compression. The same effect could be at work in Bok globules, resisting the gravitational forces that would otherwise lead to collapse. It is known that the general interstellar medium is pervaded by a weak magnetic field. Where one can make a direct estimate of the strength of the field (generally only in diffuse clouds, which are far less dense than globules) one finds that it is typically about 100,000 times weaker than the magnetic field of the earth. One would expect the magnetic field in a condensed gas cloud such as a Bok globule to be proportionately greater simply because of the globule's greater density. One can show, however, that if globules have formed by gradual gravitational condensation out of the general interstellar medium, the concomitant increase in the strength of the magnetic field will be insufficient to prevent the continuing collapse of the globule.

This simple picture of the initial condensation of Bok globules may not, however, be correct. One can perform a "thought experiment" in which the eight Bok globules in my sample maintain their mass and temperature but expand until their density equals that of the medium out of which they presumably formed. Looking at it this way it is hard to see why they would have been gravitationally unstable in the first place.

It is therefore quite possible that the globules were formed by some strong external compressive event, such as the explosion of a supernova or the passage of a galactic density wave. In such a process the weak magnetic field that undoubtedly threaded through the protoglobules would have been amplified by the compression. If that is what happened, it is entirely possible that the intensified magnetic fields, together with internal thermal pressure, are now dispersing the globules. Since there is no way to measure the strength of the magnetic field within the globules, how can this possibility be tested?

Up to a point one can again invoke the geometry of the clouds. A strong, fairly regular magnetic field within the globules would tend to make them highly elongated objects, which they are not. A more quantitative argument is provided by recent theoretical work by T. Ch. Mouschovias of Princeton University and J. M. Scalo of the University of Texas. Mouschovias has demonstrated that in general the amplification of a magnetic field in the course of the contraction of an interstellar cloud is not as strong as it was once thought to be. Scalo's work indicates that a strongly intensified field will slowly leak out of a dark cloud, a process that is accompanied by frictional heating of the gas as the field glides through it. The stronger the magnetic field in the globule is, the stronger the attendant heating must be. By calculating the contributions of the various heating and cooling mechanisms that operate within dark clouds, Scalo has shown that the magnetic fields present cannot be very strong. If they were, the globules would be considerably hotter than the 10 degrees K. inferred from the molecular observations. Although these arguments cannot be considered conclusive, they seem to place important limitations on the strength of the embedded magnetic fields available for inhibiting the gravitational condensation of Bok globules.

Turbulence

Finally one must consider the role of turbulence. Broadly speaking, turbulence refers to any irregular, eddying motion within a fluid. Because eddies must occasionally collide with each other, turbulence within a cloud will provide an additional pressure capable of resisting self-gravitation, and if the tur-

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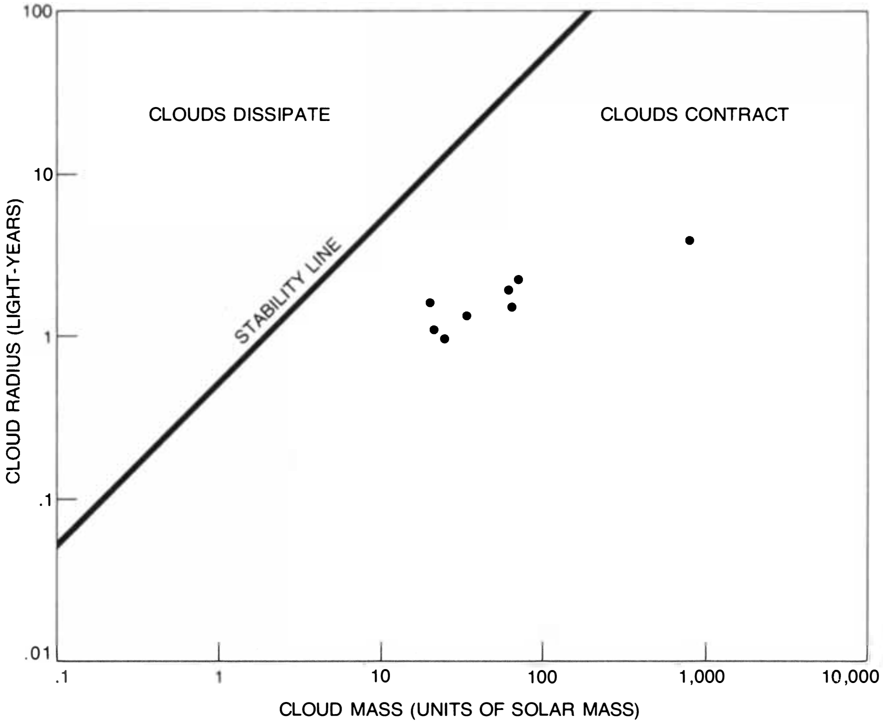
bulence is intense enough, it may disrupt the cloud entirely. Even if an interstellar cloud were perfectly static, the Doppler shifts associated with the random thermal motions of the molecules within a cloud would slightly broaden the emitted spectral lines. In the case of carbon monoxide molecules at 10 degrees K. the thermal broadening of the spectral lines is equivalent to thermal motions of about a tenth of a kilometer per second. The actual spectral lines from globules are much wider than that: they are equivalent to thermal motions of a few kilometers per second. Hence there must be sizable nonthermal internal motions in the clouds.

If turbulence is responsible for the bulk of the nonthermal line-broadening observed in Bok globules, the clouds will never collapse further. Indeed, the turbulence should be enough to disperse a typical Bok globule within the short time, in astronomical terms, of about a million years. Closer analysis, however, leads to an apparent paradox. Turbulent flows strong enough to blow a globule apart would need to have supersonic velocities. One would therefore expect the gas to be strongly heated by shock waves generated by the collisions of these supersonic flows. For the cloud temperatures to remain as low as they are observed to be the average time between collisions of the eddies must be very long. This in turn implies that the eddies must be very large, indeed so large that their turbulent structure should give rise to Doppler-shift patterns easily resolvable with radio telescopes.

If we assume that this apparent paradox rules out turbulence as the dominant cause of the nonthermal line-broadening observed in Bok globules, how else might the broadening be explained? We are led back to the process whose likelihood we have been trying to assess: gravitational collapse. Knowing the masses and present radii of Bok globules, we can calculate approximately the speed at which they are collapsing if the retarding forces of magnetic fields, rotation and turbulence are in fact negligible. The resulting free-fall collapse of the cloud must also cause spectral line-broadening, arising from Doppler-shifted molecular emission along any line of sight through the collapsing gas. Rough though such calculations necessarily are, the expected line widths due to collapse agree rather well with the observations.

On the basis of the present evidence, therefore, it seems plausible that Bok globules are gravitationally collapsing clouds and hence likely sites of star formation. Indeed, it is remarkable that the simple picture discussed here holds up so well. This is partly attributable to the essential simplicity of globules as nearly spherical, isolated units whose internal physics is far more restricted in scope than that of the massive molecular clouds. One must recognize, however, that a rigorous description of the globules must ultimately take account of all the physical processes that must be operating within them. Although rotation, magnetic fields and turbulence are probably not enough to prevent the final collapse of such clouds, these phenomena must play important roles in the clouds' evolution.



MASS-RADIUS PLOT FOR BOK GLOBULES shows where the eight globules studied by the author lie with respect to the "stability line" calculated for a cloud temperature of 10 degrees K. The simple calculation does not consider the possible existence of rotation, magnetic fields and turbulent motions that might retard collapse. According to the available evidence, these retarding forces are not present at levels high enough to offset gravitational contraction.

Seeking the New Stars

The strongest confirmation of the hypothesis that Bok globules are currently collapsing to form stars would of course be to find at least one Bok globule in which a new star or a small cluster of stars was in the process of being born. The probability of such a discovery is low because a typical globule has a mass only 100 times that of the sun. The mass of a typical large molecular cloud associated with an H II region, where stars are definitely known to form, is tens of thousands of solar masses.

Recently, however, W. E. Herbst of York University and D. G. Turner of the University of Toronto have reported that a globule known as Lynds 810 (which is not included in my study) appears to have embedded within it a young, fairly hot star and possibly several such stars. The stars (if there is more than one star) are intimately associated with nearby interstellar gas and dust, out of which they may have formed. The dust scatters the light of the embedded stars to create a small reflection nebula, apparently associated with the globule. It is tempting to speculate that the stars recently formed from the globule itself. At the distance assigned to it by Herbst and Turner, Lynds 810 appears to have a radius of four or five light-years, making it slightly larger than Barnard 5, the largest globule in my sample. Molecular-line observations are now being made at the Aerospace Corporation to see if Lynds 810 resembles Barnard 5 in mass and temperature.

The possibility that at least the more massive Bok globules such as Barnard 5 may ultimately give rise to stars with surrounding reflection nebulas is exciting. Recently M. L. Kutner of the Rensselaer Polytechnic Institute, K. D. Tucker of Fordham University and I have undertaken a comprehensive molecular-line study of interstellar clouds associated with reflection nebulas. With carbon monoxide observations of these clouds it should be possible to determine their mass. If some of these objects turn out to have masses on the order of 100 to several hundred solar masses, it will be difficult to avoid the conclusion that the more massive Bok globules are indeed active sites of star formation.

Spatial Memory

Among the many things animals are able to remember is where they have been. Experiments with rats suggest that this kind of memory is localized in the region of the brain known as the hippocampus

by David S. Olton

The ability of an animal to keep track of its location in space by remembering where it has been is a basic component of intelligent behavior. According to modern concepts of memory, this ability involves a form of short-term memory, called working memory, that stores information as it is being worked on, or processed. (A common verbal example is remembering a telephone number obtained from a directory as you dial the number.) How is spatial memory programmed? Is it localized in some specific part of the brain? Is it associated with the activity of specific nerve cells? Such questions have now been at least partly answered by psychological and physiological experiments with rodents.

The importance of spatial memory for the survival of an animal is suggested by the behavior of the Hawaiian honeycreeper, a bird that feeds on nectar from flowers. Each of the flowers in the bird's territory may provide nectar on numerous visits, but the supply of nectar on any one visit is limited and time must pass before it is replaced. If the bird returns to the flower during this time, it finds little or no nectar. The optimal strategy is therefore to visit the other flowers before returning to the first one, giving each flower the longest possible time to replace its nectar. Alan C. Kamil of the University of Massachusetts, who has studied the Hawaiian honeycreeper in its natural habitat, has found that it tends to follow such a strategy: it does significantly better than chance at remembering the locations of flowers it has recently visited, rarely returning to them until enough time has passed for the nectar to be replenished.

The importance of spatial memory has also been demonstrated by laboratory experiments. When rewards and punishments are consistently located in a particular place, experimental animals quickly learn to obtain the rewards and avoid the punishments. Even when the rewards and punishments are correlated with some stimulus other than spatial location (such as a light), the animal will still attempt to solve the task first on the basis of its spatial characteristics, for example consistently turning right or left rather than responding to the location of the light. Only after the attempt at a spatial solution has failed does the animal begin to try other strategies.

To obtain some understanding of how animals use working memory to solve spatial problems, my colleagues and I at Johns Hopkins University developed a new experimental procedure that would enable us to study working memory. We based our experimental design on the spatial maze, an apparatus that has been employed for testing animal behavior since the turn of the century. Such mazes vary considerably in complexity, from a simple *T* to a miniature replica of the famous hedge maze at Hampton Court outside London. The late Edward C. Tolman of the University of California at Berkeley was a strong advocate of using mazes to explore the cognitive abilities of animals; he believed the major component of an animal's solution of a problem is its ability to discover the experimenter's instructions. Mazes are particularly useful in this regard because the instructions are inherent in the apparatus itself.

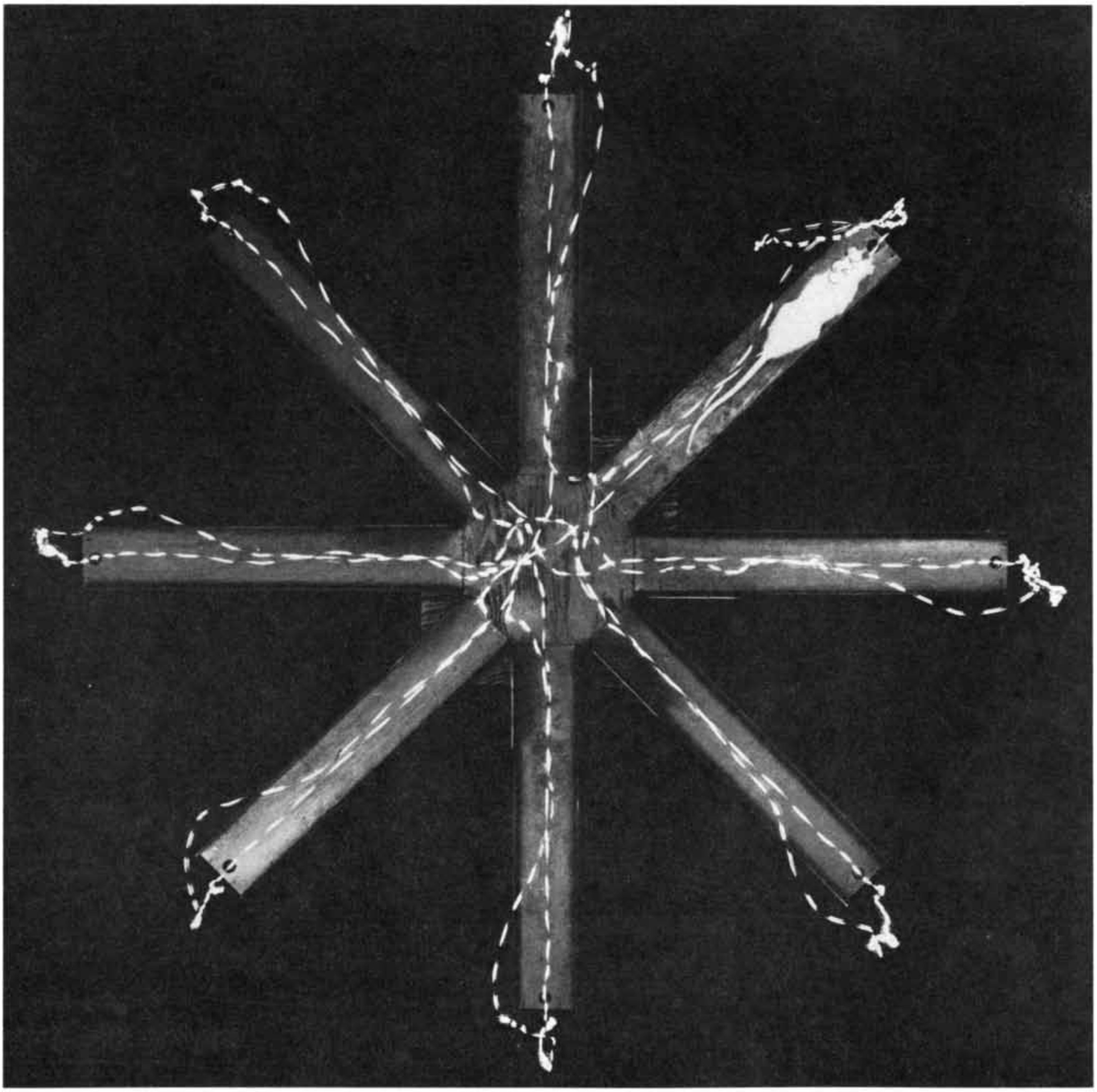
In our experiments we wanted to give rodents instructions that were essentially the same as the spatial strategy of the honeycreeper: Remember a list of places where food can be found and then visit each place once before returning to the first one. To make these instructions clear to the animals we developed a maze with eight radiating arms elevated on stilts. At the start of a test a food pellet was placed at the end of each arm. The animal was then put in the center of the apparatus and allowed to choose the arms freely until it had obtained all eight pellets. The optimal strategy is clearly to visit each arm once and not to return to it, thus visiting all eight arms in the first eight choices. In this way the animal can get the eight food pellets with the least amount of running through the maze.

So far the animals we have tested in the radial-arm maze have been mostly laboratory rats, but we have obtained similar results with the first-generation offspring of wild rats and with gerbils. All the animals learned rapidly and performed well. After a few days of being trained to run on the elevated alleyways, they made an average of 6.8 correct responses in the first eight choices; after 20 days they had improved to an average of 7.8 correct responses. Since the animal returned to the center platform after each response and therefore had all eight arms available on every choice, the probability of its making at least seven correct responses by chance in the first eight choices was very low (.07). Yet by the end of the testing every animal performed this well for 10 consecutive days (a probability of $.07^{10}$), making it extremely unlikely that mere chance was involved in its performance.

There were two main theoretical explanations for the excellent performance of rodents in the radial maze. Either they were identifying the position of the visited arms by comparing them with landmarks in the surrounding room or they were following some simpler strategy that required them to store a smaller amount of information in their working memory. One such strategy would be to use an algorithm, or rule, such as "Choose adjacent arms in a clockwise direction." Only the general strategy would have to be kept in the working memory; the specific arms chosen could be forgotten immediately after each choice. Another strategy would be to use the rodent equivalent of a check mark, perhaps a scent label left at the entrance to a visited arm. The particular choice could then be forgotten because the label would serve as a permanent reminder.

The algorithm hypothesis was easy to dismiss because the daily sequence of choices was not consistent enough for the accurate choice behavior to depend on a particular rule. The possibility that the rats were marking visited arms with a label of some kind was harder to evaluate and required an additional experiment. For this purpose we regarded landmarks in the surrounding room and the hypothetical labels within the maze as being "relevant-redundant" cues: relevant, because either might guide choice behavior, and redundant, because in the usual testing situation both cues always occurred together. In order to evaluate the relative importance of the two types of cue we separated them and made them nonredundant. We did so by allowing the animal to make three choices and then rotating the maze (with the animal confined in the center) to a new position, thereby separating the place cues (which remained the same) and the hypothetical labels (which moved with the maze). The three arms already chosen were rebaited so that all the arms again contained food pellets, and the animal was allowed to choose freely among the arms until it had chosen five more of them (for a total of eight). We found that the animals tended to avoid the first three spatial locations, even though the maze rotation had placed arms that had not previously been visited and hence would have lacked labels in these locations. The results therefore indicated that the animals were not following a maze-labeling strategy.

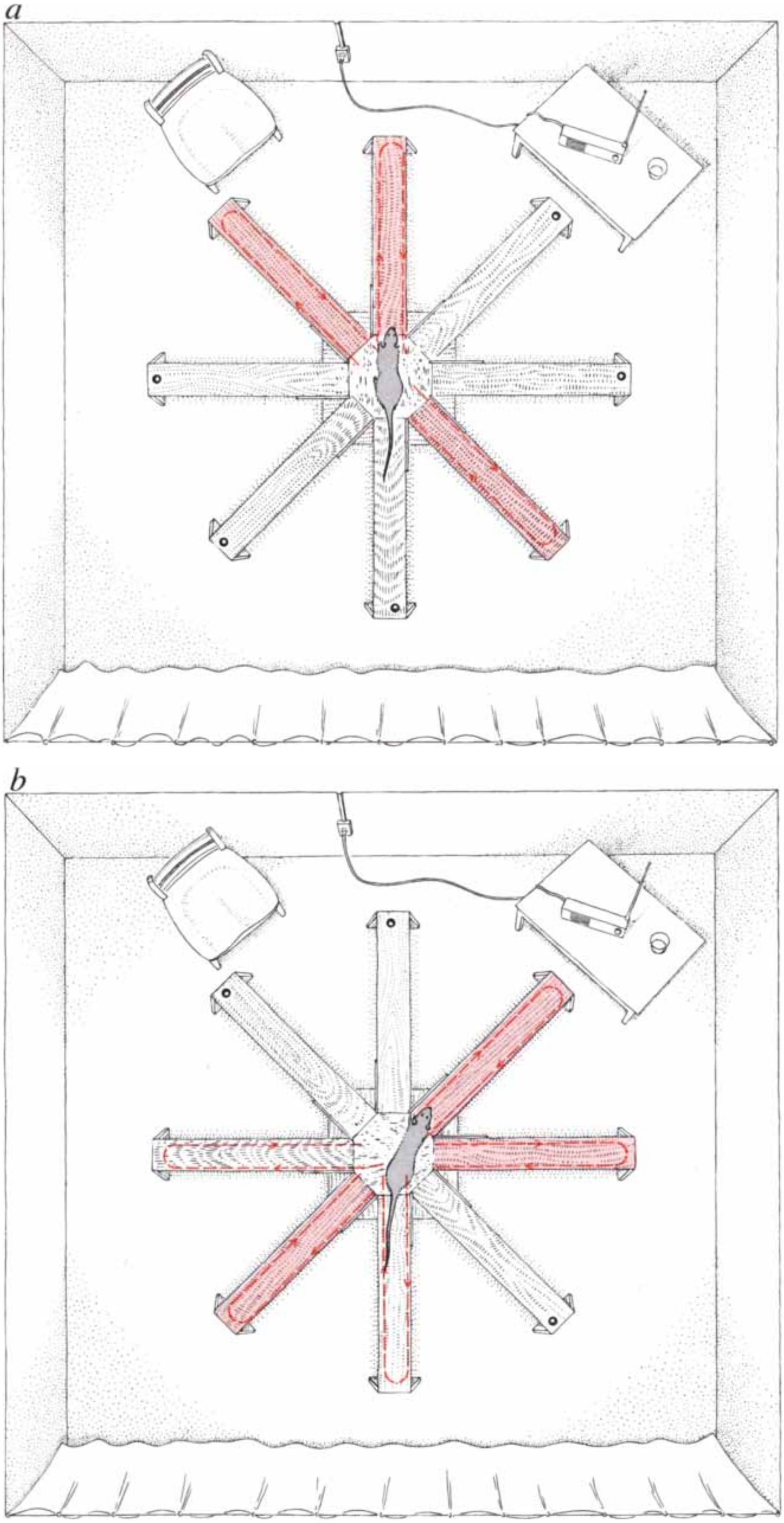
We next wondered whether the rats were learning a spatial map that enabled them to understand the relations among all the parts of the maze, or whether they were simply learning some kind of list of places that were unrelated and independent. To determine which was the case John A. Walker, a graduate student at Johns Hopkins, designed a testing procedure with a four-arm maze. The rat was first placed at the end of an arm and allowed to obtain the food pel-



PATH OF NORMAL RAT as it travels through an eight-arm spatial maze is shown in this two-minute time exposure made in the author's laboratory by affixing a flashing light to the animal's head. Optimal strategy is to visit each arm once, picking up food pellet at the far end. This task requires the animal to keep track of the spatial locations it has visited by storing them in short-term, or "working," memory.

a

b



MAZE-ROTATION EXPERIMENT shows that rats do not identify visited arms by marking them with a pheromone, or scent. The rat was first allowed to choose three arms (*a*). The maze was then rotated until the chosen arms (*color*) were correlated with unchosen spatial locations. The arms were rebaited and the animal was allowed to make five more choices (*b*). Instead of avoiding arms previously visited (as the scent-marking theory would predict) the animal chose the five unvisited spatial locations even though that meant returning to visited arms. This suggests that the animals remember arms by correlating them with stimuli in surrounding room.

let there rather than having to run out on the arm of its own accord. After the initial placement the animal was returned to the center platform and allowed to choose among the arms freely. The animal could therefore remember where it had been only on the basis of spatial stimuli at the end of one arm and had to make the rest of the choices on the basis of stimuli at the entrance to the arms. Only by successfully making the association between the two sets of spatial stimuli could the animal correctly solve the problem.

We found that the animals had no difficulty with this procedure. After a few days of adapting to being placed at the end of the arms, they chose just as well as they did in the usual procedure and did not return to the arm on which they had been placed. These results suggested that the animals had indeed learned a map of the maze that enabled them to understand the spatial relations between the various parts of it. Moreover, since the animals were placed at the end of an arm, they never had the opportunity to leave a label identifying that arm, again demonstrating the absence of an intramaze labeling strategy.

To further explore the nature of the spatial memory we did a series of experiments to see if the animals' memory for the list of visited arms had some characteristics in common with those described for human learning of items in a list. One of these characteristics is that the capacity of working memory is limited: the more items that are stored, the worse the memory for those items is. When we tested rats on the eight-arm maze and also on a 17-arm maze, we found in both there was a significant decline in the probability of a correct response as the number of choices increased.

There were two possible theoretical explanations for the decline in accuracy of choice behavior during a test. The first was that the memory trace gradually decayed with time, rather like a fading photograph, so that the memory of the early choices diminished toward the end of the test and increased the likelihood of a return to those arms. The second was that information was not forgotten because of the passage of time per se but because the storage of the earlier choices in working memory interfered with the storage of the later choices. In order to distinguish between these two explanations we separated time and choices by varying the amount of time required for the animals to complete a test.

In some experiments we approximately doubled the duration of the test by placing guillotine doors at the entrance to each arm. The doors were lowered after each choice, confining the animal to the center of the maze for about 20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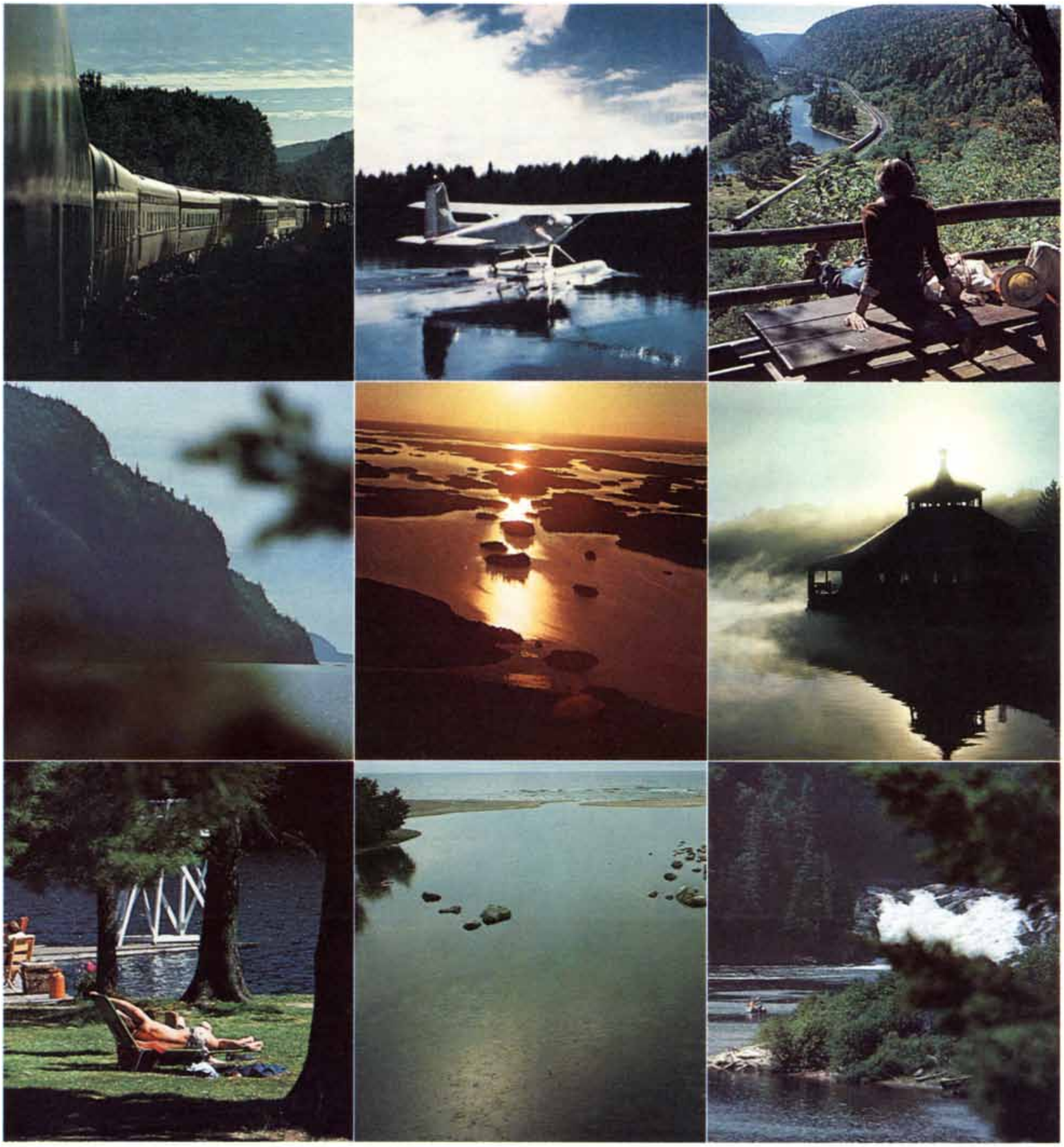

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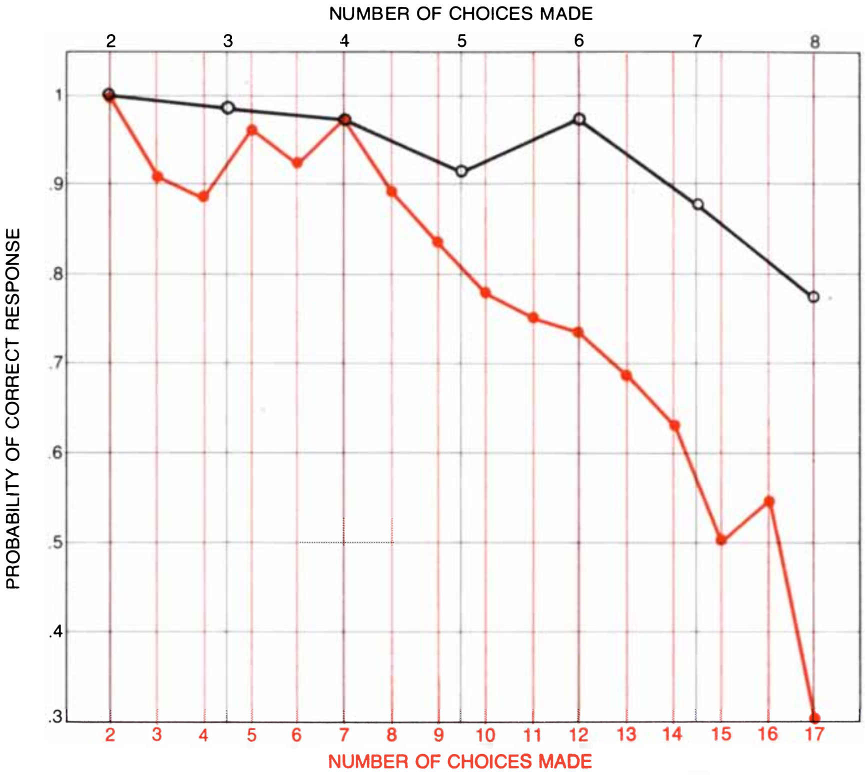
seconds. In other experiments the testing time was cut approximately in half by providing the animals with water on the central platform, facilitating the ingestion of the dry pellets. Under these conditions the memory-trace-decay hypothesis would predict that the animals would perform better than normal when the test was shorter and worse than normal when the test was longer, whereas the interference theory would predict that such manipulations would have no effect because the number of choices the animal made was not altered.

We found that the animals performed no better or worse than usual when the testing time was shortened or lengthened. Moreover, additional experiments demonstrated little or no decay of spatial working memory for periods of up to an hour. Thus it appears that short-term forgetting in this task results from interference among the items to be remembered rather than from a decay of the memory trace.

Another characteristic of working memory we have examined is the effect of the order in which items are entered in memory. As an example, consider having to learn a list composed of the following eight words: house, cat, car, love, desk, wall, card, patch. If you are like most people, you will remember the first two words on the list and the last two words better than the words in the middle. Hence the order in which items are entered into memory may affect the accuracy of their recall.

With this human psychological phenomenon in mind we looked for a serial-order effect on the spatial-memory store in rodents by examining choice performance to see whether the animals made fewer mistakes involving the first few or the last few choices in a test. Such a distinction did not seem to be present; when there was an error, it was as likely to be made by repeating the first or the last choices as by repeating choices in the middle. Thus either rodents do not store their spatial choices in a particular serial order or serial storage does not affect the accuracy of their recall as it does in man.

Finally, we investigated the ability of the animals to isolate spatial information from one test so that it did not interfere with their performance on a later test. Since the capacity of working memory is limited, it should ideally be cleared of all old and unnecessary information as rapidly as possible so that a maximum amount of new information can be stored. In experiments with human subjects this process is called resetting. To determine whether rodents could also reset working memory by eliminating old information at the end of a test we gave the animals eight tests on the eight-arm maze in immediate succession, letting the animal know a given test was over by removing it briefly from the apparatus. We found that although accuracy of choice among the arms decreased as we expected within each test as the number of choices increased, it recovered markedly at the beginning of the next test, indicating that the animals were indeed resetting their working memory between tests.



ACCURACY OF CHOICES DECLINES in a test as the number of correct choices increases, a phenomenon that can be observed both in the eight-arm maze (*black*) and the 17-arm maze (*color*). Experiments by the author suggest that this decline is due to an interference among the items stored in working memory rather than to a time-dependent decay of the memory trace.

Once we had achieved our aim of establishing an adequate test of spatial working memory in animals we turned our attention to the brain mechanisms underlying this kind of memory. We were particularly interested in the region of the brain named the hippocampus (after the Greek for sea horse, which it resembles in curving around the core of the brain). Experiments I had conducted with Robert L. Isaacson at the University of Michigan had suggested that following damage to the hippocampus rats have difficulty distinguishing between the left and the right half of a simple maze, whereas normal animals do not. Several other investigators, particularly Helen Mahut of Northeastern University, also noted the peculiar difficulty animals with damage to the hippocampus had with spatial tasks.

The first formal theoretical statement of the role of the hippocampus in spatial behavior was made by John O'Keefe and Lynn Nadel of University College London, who provided experimental evidence that the hippocampus forms the spatial map animals use to guide themselves through space. In one experiment with Abraham H. Black of McMaster University they trained rats to run from one small compartment to another to avoid shock. They found that normal animals learned to associate the shock with the spatial location of the compartment in the room but that rats with damage to the hippocampal system appeared to ignore completely the spatial characteristics of the task. Since rats in the radial-arm maze rely on spatial information to choose each arm, we thought it would be valuable to observe the effect of experimental damage to the hippocampus on the accuracy of choice.

Rats have a large and well-formed hippocampus, and its connections to other parts of the rat brain have been extensively studied by Walle J. H. Nauta of the Massachusetts Institute of Technology and Theodor W. Blackstad of the University of Aarhus. A major connection is in the entorhinal cortex, which lies in back of the hippocampus and connects it to the areas of the cerebral cortex that are involved in processing sensory information. A second connection is by way of the fornix (meaning arch) to the deep brain structures involved in motivation and emotion. The fornix is divided into two parts: an upper part that passes through the septum in the center of the brain and is called the precommissural fornix, and a lower one that bypasses the septum and is called the postcommissural fornix. The region where the two parts join is called the fimbria-fornix.

In our experiments the animals were first trained in the radial-arm maze until their performance was stable. Then they were anesthetized and lesions were made surgically by cutting one of the hippocampal connections. Control animals underwent all the surgical procedures except the production of a lesion. After several days for recovery from the surgery the animals were retested in the radial-arm maze. There were two test periods: one beginning four days after surgery to examine the acute effects of the brain lesion and the other beginning 50 days after surgery to determine whether the behavioral deficits produced by the lesion might diminish with time. In both cases we wanted to know whether an animal that had been operated on could perform as well as one that had not, and if it could not perform as well, exactly how its performance was affected by the brain damage.

In the control animals there was no significant effect of the surgery itself. Lesions in the cerebral cortex, an area not immediately related to the hippocampus, had essentially no behavioral effect. Destruction of any part of the hippocampal system, however, caused a profound impairment in maze performance both during the testing period immediately after surgery and during the testing period 50 days later. Lesions in the caudate nucleus, another nonhippocampal area, had a slight disruptive effect but not one of the same magnitude as lesions in the hippocampus.

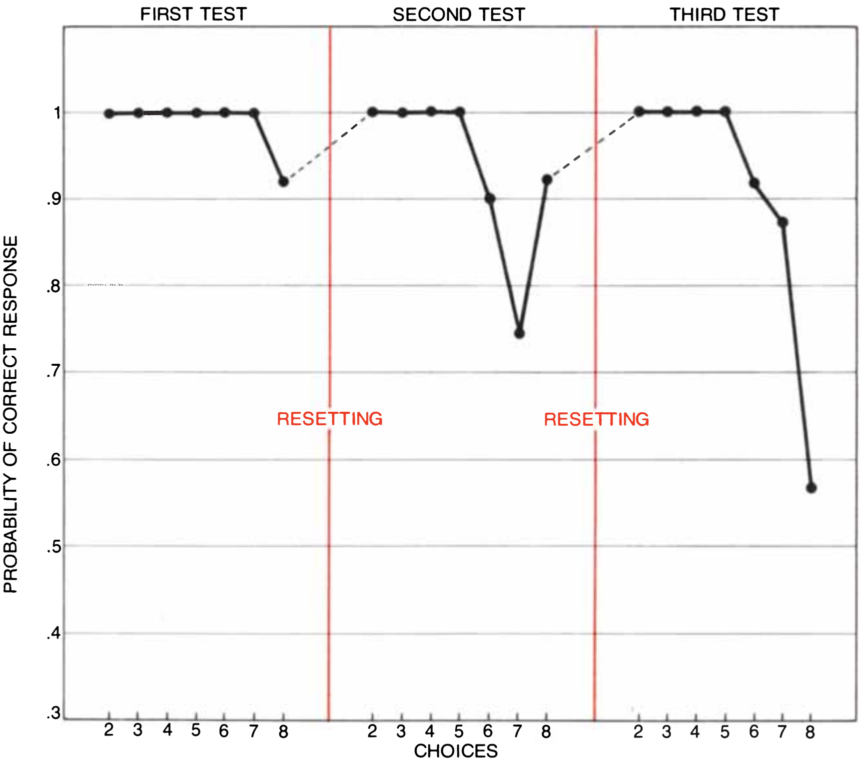
The lack of major effects of damage in other brain areas indicates that impairment of spatial performance is not caused by disrupting just any system in the rodent brain; it seems to be particularly associated with damage to the hippocampal system. Another point of interest is the similarity in the degree of the deficit after the destruction of each connection to the hippocampus. One could postulate many different circuit diagrams of hippocampal function, but the fact that behavior is disrupted in the same way after any lesion in the hippocampal system limits the number of acceptable alternatives.

The changes produced by the lesions appear to be irreversible, even though the hippocampus has proved to be a very "plastic" brain area, reorganizing itself after many different types of damage. Gary S. Lynch of the University of California at Irvine and Oswald Steward of the University of Virginia have demonstrated that after destruction of either the body of the fornix or the entorhinal area many of the fibers in the hippocampus sprout and put out new connections in a few days. Since in our experiments the animals did not perform any better 50 days after surgery than they had immediately afterward, plastic changes in the hippocampus appear to have no functional importance for the animal in this type of task.

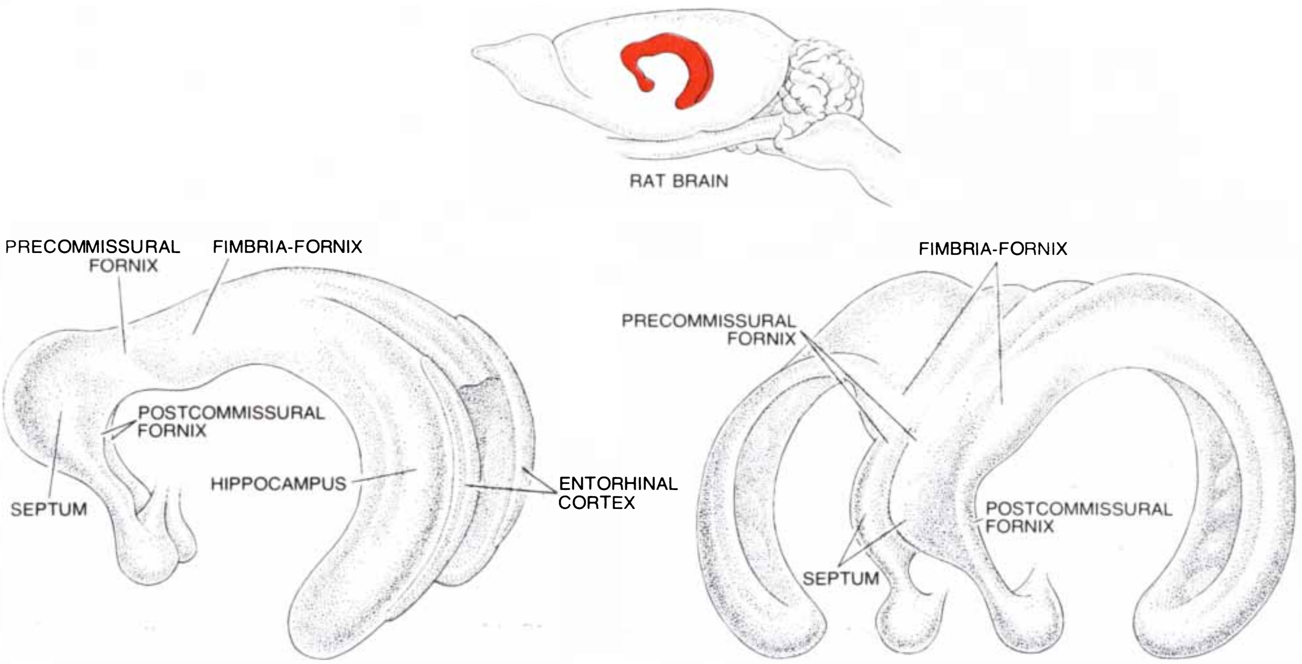
Having shown that animals with their hippocampal function disrupted by lesions had great difficulty performing well in the radial-arm maze, we attempted to characterize the difficulty. Several possible explanations were quickly eliminated. After brain damage the animals were just as coordinated in the maze as before and showed no tendency to fall off the arms or miss them altogether. In fact, the animals ran slightly faster than usual and with no hesitation, indicating that the impaired choice behavior did not result from some primary sensory or motor deficit.

Many experiments, such as those of Isaacson (who is now at the University of Florida), have characterized animals with hippocampal damage as "perseverating," or returning to make the same error time after time, more often than would be expected by chance. In our experiments too animals with damage to the hippocampus exhibited remarkable repetitions of choice sequences, a behavior that was almost never observed in normal animals. One rat, for example, chose arms 2, 4, 6 and 8 on the first four choices and then repeated the same sequence twice more before making the next correct response. Another animal chose opposite arms, responding first to Arm 1 and then to Arm 5, and repeated the sequence five times. These are the types of behavior one would expect if the animals were actively perseverating in their choices.

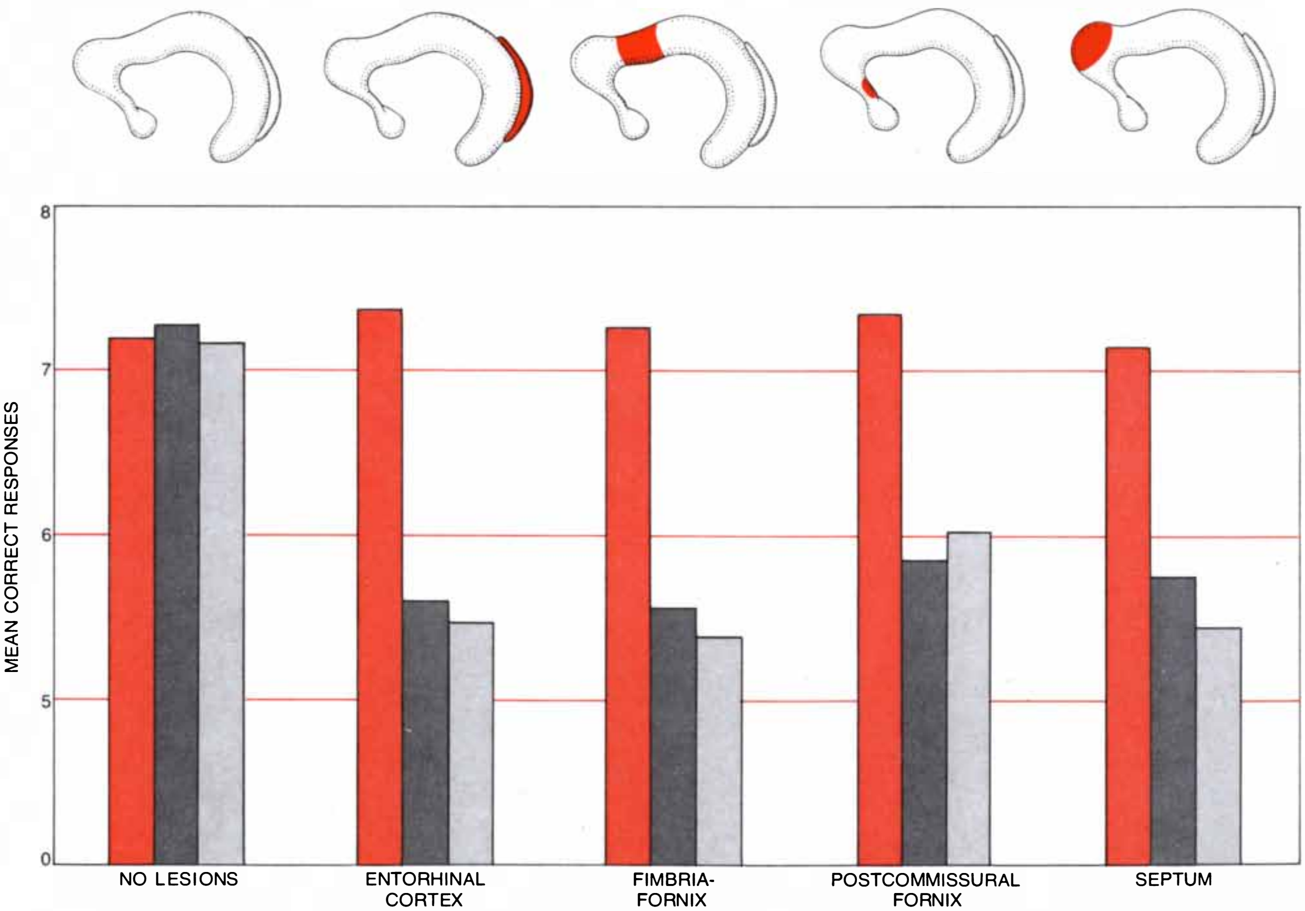
The significance of perseveration is still an open question. At present there seem to be two alternative explanations for this striking effect of lesions in the hippocampus. First, it is possible that damage to the hippocampus does not destroy spatial memory but instead disrupts other cognitive functions. In that case the animal would be able to discriminate between correct and incorrect choices but its decision-making ability would be out of phase, like that of a speculator in the stock market who consistently buys long before a stock goes down and sells short before a stock goes up. The second possibility is that the lesions in the hippocampus do destroy spatial memory and that the rats, instead of behaving on the basis of spatial stimuli, try to compensate by using a different set of stimuli to control their



OLD INFORMATION IS CLEARED from working memory after each test in the spatial maze so that a maximum amount of new information can be stored. Called resetting, this process was demonstrated by giving a rat a series of tests in the eight-arm maze (removing the animal briefly from apparatus between tests). Choice accuracy returned to maximum level at the beginning of each test, indicating that old choices were not interfering with new ones.



HIPPOCAMPUS is a structure in the center of the rat brain. It is named after the Greek word for sea horse because it is shaped somewhat like one. It is connected to deep brain structures by way of the fornix and to higher brain structures by way of the entorhinal cortex.

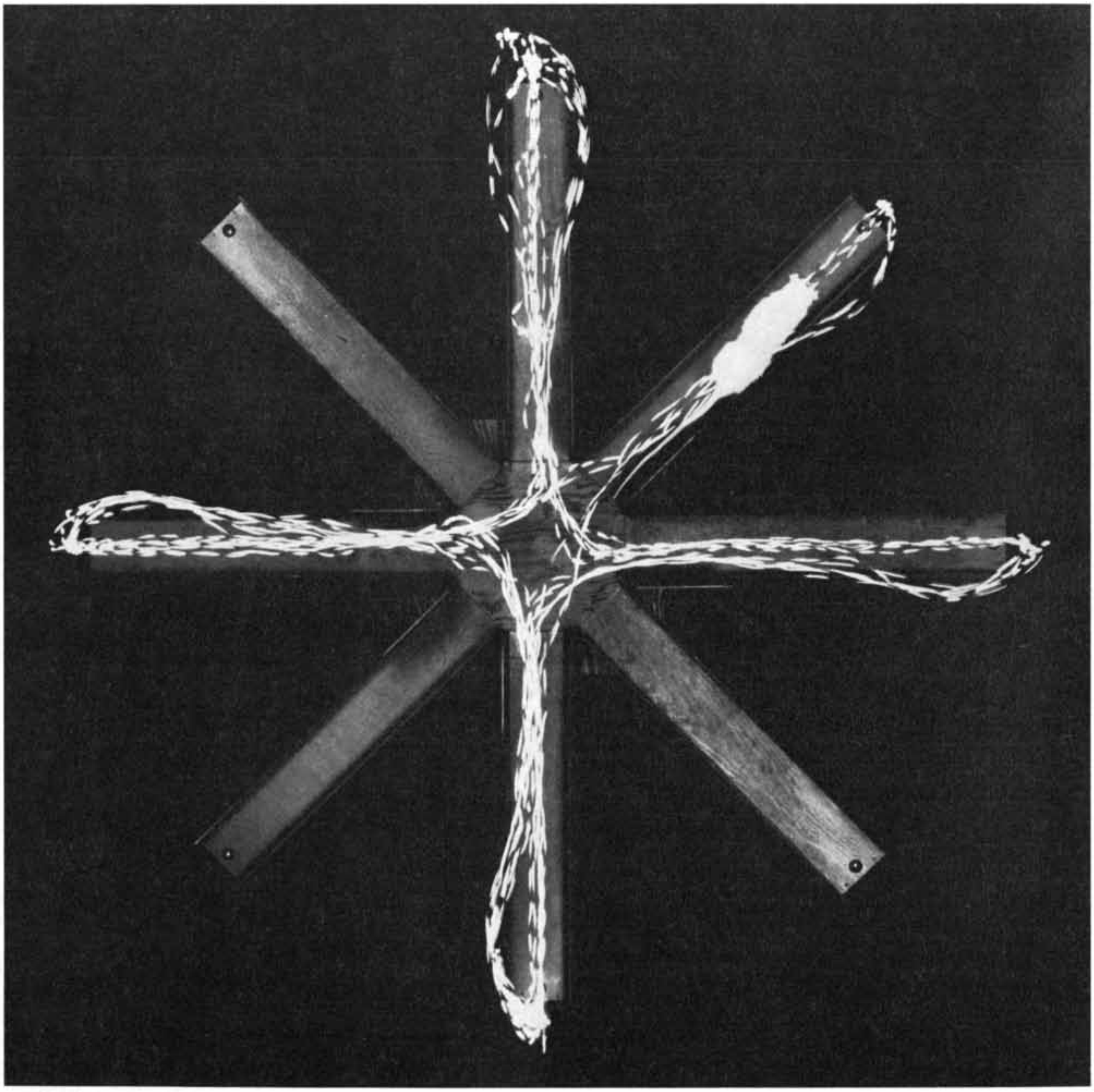


LESIONS IN THE HIPPOCAMPUS cause rodents to perform poorly on radial-arm maze compared with normal performance (*color*), suggesting that the hippocampus is essential for spatial working memory. The disruptive effect is specific to the hippocampus (lesions in other brain regions have little or no effect) and is the same four days after surgery (*dark gray*) or 50 days after it (*light gray*). Damage to any part of the hippocampal circuit produces a similar behavioral disturbance, limiting the number of possible "circuit diagrams."

behavior, such as a learned sequence of muscular movements or a place-cue strategy.

To understand this latter concept consider a person in New York City who wants to travel first to San Francisco, then to Miami and then back to New York. If he has formed a cognitive map of the U.S., he knows that San Francisco is west of New York and Miami is south. Therefore he would know that he should drive west to San Francisco and then in a southeasterly direction to Miami. The traveler could also make the trip, however, without having any idea where he is. Instead of relying on his knowledge of geography he could follow a cue strategy based on the fact that New York and San Francisco are connected by Route 80 and New York and Miami are connected by Route 95. That strategy would be successful in getting him to his destination, but once he was in San Francisco he would have no idea how to get directly to Miami, and he would have to retrace his path by way of Route 80 to New York and then take Route 95 south to Miami.

O'Keefe and Nadel have suggested that the hippocampus is responsible for creating the spatial map and that other brain structures mediate cue learning. To support their view they conducted an experiment testing two groups of rats in a circular maze. One group was trained to use spatial stimuli, as in our usual experiments with radial-arm mazes. The other group was given an explicit cue (a stand with a light on it) to mark the location of the food. Normal animals and animals with lesions in the fornix were trained in both tasks. The fornix lesions produced the expected behavioral deficit in the group that learned with spatial stimuli but had little effect on the group that learned with the light cue. These results suggested that if we could modify the radial-arm maze to make it a cue-



ABNORMAL MAZE BEHAVIOR of a rat with a lesion in the fornix is shown in this time exposure. The striking repetition of a sequence of choices, termed perseveration, is often seen in such animals. It may be that damage to the hippocampus destroys the animal's ability to learn a cognitive map of the maze, forcing it to rely on a simpler strategy such as repeating a sequence of muscular movements.

learning task rather than a spatial one, animals with fornix damage should perform no worse than normal animals.

To test this prediction we altered the 17-arm maze so that it could be solved by cue learning. At the outside end of each arm we put a small drawbridge that was an extension of the arm and could be raised or lowered. The food pellet was placed on a pedestal beyond the end of the arm so that the animal had to cross the bridge to get the food. At the beginning of each test the drawbridge on every arm was raised. When the animal went out on an arm to get food, it pushed the drawbridge down, ran across it to pick up the pellet and then returned to the center. The drawbridge stayed down for the remainder of the test, so that the rat did not have to remember each of the arms chosen because the position of the drawbridge could function as a cue to guide his choices correctly. When the rat was deciding which arm to choose next, it needed only to look down each arm. If the drawbridge was up, the rat would know it should choose that arm.

So far we have only preliminary evidence from a few animals, but the results strongly support O'Keefe and Nadel's predictions. All the rats were first trained to respond correctly, one group with drawbridges and the other without. Lesions were then made in their fornix. Rats tested in the usual spatial procedure without the drawbridge cues showed a severe impairment after the lesions and performed no better than chance even on the second choice. Lesioned rats tested with drawbridge cues, on the other hand, showed at most only a transient impairment that might have been due to the effects of the operation itself. Within a few days they were performing without error, choosing only those arms with the drawbridge up and avoiding all the arms with the drawbridge down. These results demonstrate that animals with damage to the hippocampus show an impairment only in those procedures that might involve spatial memory, not in every testing procedure in the radial-arm maze. When rats with lesions in the hippocampus are given an alternative strategy based on cue learning, they have no difficulty in performing as well as normal animals.

Another way of approaching the relation between brain structures and behavioral functions is to obtain recordings of brain activity while the animals are engaged in the appropriate behavior. If the brain structure is important in the function required for the performance of the behavior, the electrical activity of the nerve cells making up the structure ought to be correlated with that behavior.

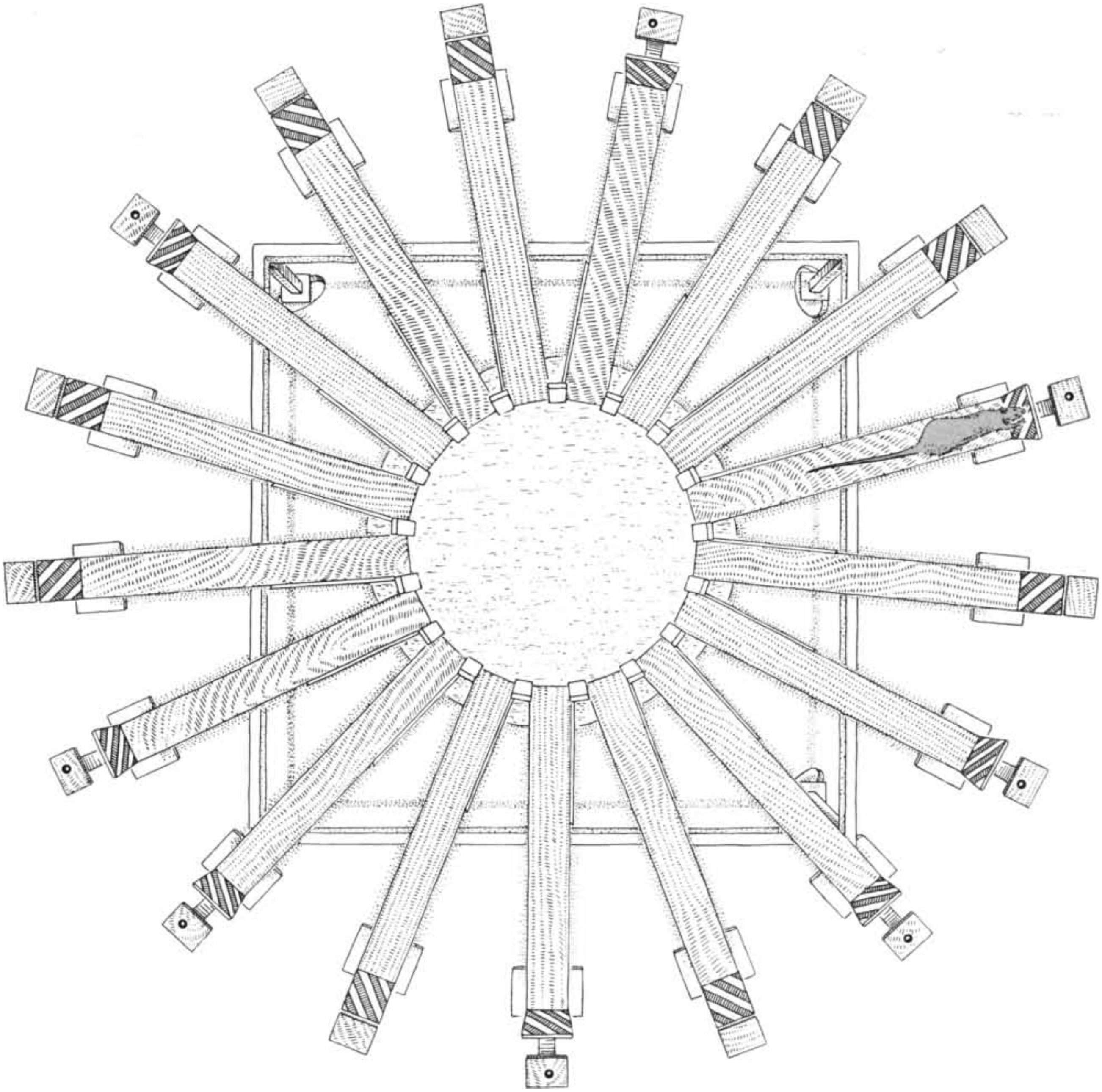
James B. Ranck, Jr., of the Downstate Medical Center of the State University of New York and O'Keefe, Nadel and their colleagues have obtained considerable information about the types of behavior that are correlated with electrical activity in the hippocampus. Most relevant to our maze experiments are O'Keefe's findings that the activity of some cells in the hippocampus is strongly correlated with the animal's position in space. O'Keefe called these cells "place units" to emphasize the fact that their activity depended on the animal's position in the apparatus and not on the type of behavior being displayed by the animal in that position. Whether the animal was eating, drinking, grooming, running or just standing still seemed to make no difference to the cell. As long as the rat was in a particular place in the apparatus the cell was active, and whenever the rat left that place the cell was quiet.

Since rats use spatial stimuli to solve the radial-arm maze, we decided to search for place units in the hippocampus while the animals were running in the maze. To test the hypothesis that nerve cells in the hippocampus mediate spatial memory in our task I collaborated with Phillip J. Best and Michael H. Branch of the University of Virginia on a series of neurophysiological experiments. We first trained animals in the radial-arm maze with a procedure of partial reinforcement in which food was placed randomly at the ends of the arms. The optimal strategy for the animal was thus to move continually about the apparatus, checking the end of each arm to determine if food had been replaced there. The animals learned this behavior quite rapidly, and for periods of several hours they would regularly explore all the arms of the maze.

We then surgically attached a microelectrode mounting to each animal's skull. The mounting, developed by Ranck, was very light and caused no discomfort or interference. Several days after surgery we attached a tungsten wire microelectrode to the mounting and lowered it into the brain. All but three microns (three thousandths of a millimeter) at the tip of the electrode was insulated, so that we could record from single nerve cells. The insertion procedure was essentially blind: we merely lowered the electrode into the hippocampus until the activity of a single cell was detected. After the recording experiment had been completed we made a spot lesion by passing a relatively small amount of current through the tip of the electrode. Hence we were later able to identify the precise area of the hippocampus we had been recording from by slicing the brain and staining the tissue.

When we located a cell in the hippocampus with the electrode, the rat was allowed to run freely in the radial-arm maze while the cell's activity was recorded, amplified and displayed on an oscilloscope screen. We found that many cells in the hippocampus responded selectively to certain arms of the maze either by an increase in their rate of firing when the rat chose an arm or by an abrupt decrease in the rate of firing below the average level of activity. One cell, for example, was relatively inactive when the animal started on Arm 5, became very active on arms 2 and 3, quieted down on the other arms and became active again on arms 2 and 3.

Using this procedure and recording for periods of several hours with each cell, we classified arms as being either "on" or "off." This usage followed one that is generally applied to the receptive fields of nerve cells in the visual or auditory regions of the cerebral cortex to identify the types of visual or auditory stimuli that cause these cells to modify their firing rate significantly. In our experiments an "on" arm was an arm in the maze where the cell fired more rapidly; an "off" arm was one where the cell fired more slowly. For an arm to be considered either "on" or "off" it had to meet two criteria. The first was that the mean rate of activity when the animal was on the arm had to be at least three standard errors of the mean greater or less than the overall mean rate, since the likelihood of a rate change that large occurring by chance is very small (.002). The second was that the mean rate of activity on an arm had to be consistently different from the overall mean rate each time the animal entered the arm, so as to ensure that the large increased or



ADDITION OF DRAWBRIDGES enables animals to successfully solve the 17-arm maze without having to learn a cognitive map of its layout in space. At the start of a test the drawbridge at the end of each arm is up and the animal must push it down and run across it in order to obtain the food on the pedestal beyond. The lowered bridge serves from then on as a visual cue, informing the animal that it has already visited an arm. Rats with lesions in the hippocampus perform poorly in conventional mazes but perform well in modified maze. This result suggests that although the hippocampus is required for learning a cognitive map of the environment, other brain regions mediate simpler strategies (such as cue learning) that enable the animal to find its way through the spatial maze without knowing where it is.

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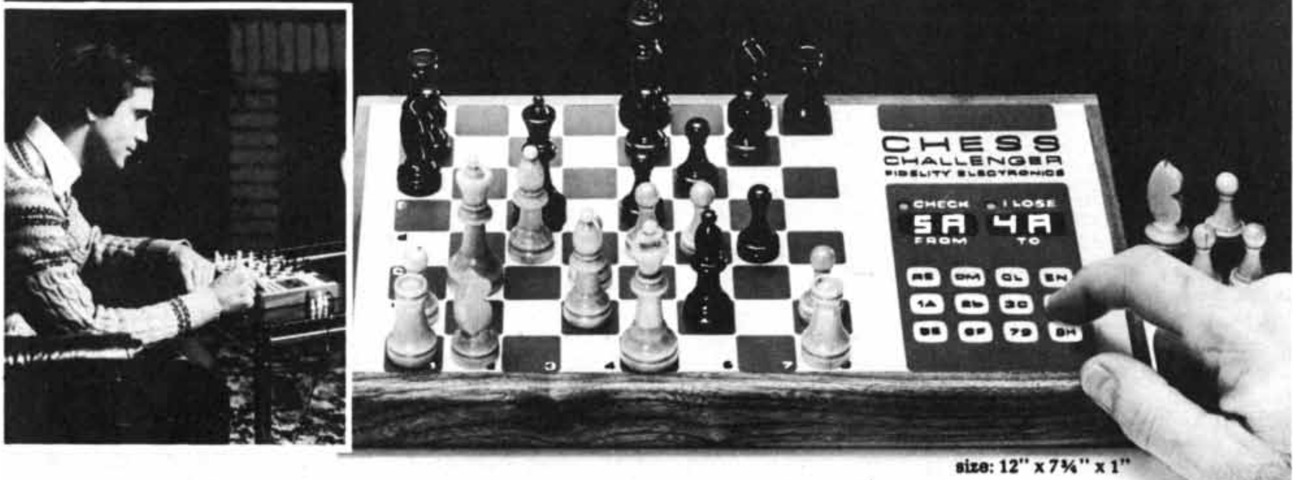

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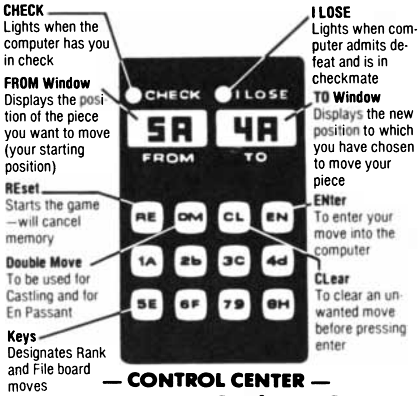

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decreased rate of firing was not a random effect but was consistent over a period of time.

For example, for one cell we recorded from, arms 2 and 3 passed both criteria for being an "on" arm, arms 1, 4, 6, 7 and 8 passed both criteria for being an "off" arm and Arm 5 did not meet at least one of the two criteria. The receptive field of this cell therefore divided the radial-arm maze into a small "on" field and a larger "off" field.

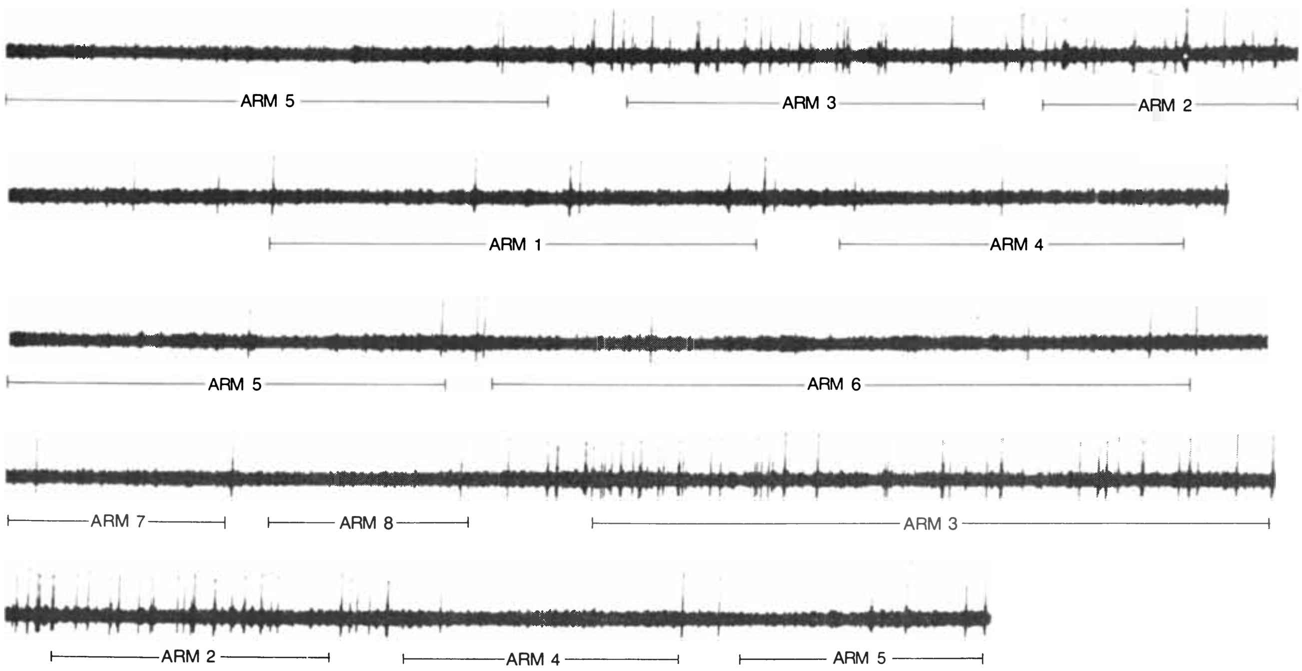
How do we know that the only behavioral correlate of a hippocampal cell's activity is the animal's position in space? The answer is that we do not. One of the difficulties with any recording experiment is that the investigators do not have the time or the opportunity to ask the cell about every possible stimulus. In short, one can never be certain whether one has found the only behavioral correlate or receptive field of a given brain cell. We did, however, carry out a number of tests to ensure that some irrelevant part of the experimental procedure was not particularly influencing the cell's activity. We distracted the animal in various ways, picking it up, clapping our hands, flashing lights and moving around in the testing chamber and the adjoining room. We altered the animal's expectations about reinforcement by attracting it to an arm with food held in front of it with tweezers, by placing food in unusual positions in the maze (such as in the middle of an arm) or by occasionally putting food at the end of the arm only after the animal had already checked the food cup and found that it was empty.

Throughout all of these modifications the activity recorded from the cell in the hippocampus was stable; the only obvious behavior that was correlated with the amount of activity in the nerve cell was the position of the animal in the maze. This was true even when the general motivation of the animal changed as the animal became satiated. Running behavior clearly waxed and waned in cycles, the animal sometimes responding slowly and pausing to groom itself or to rest, and sometimes responding rapidly and running through all eight choices in about 30 seconds. Still the activity of the cells in the hippocampus remained consistent. As a final control we also recorded from cells in other brain structures and found no correlation between spatial location and the cells' firing rate. In short, the cells we recorded from in the hippocampus looked just like those O'Keefe described as place units. The activity of the cell was correlated with the animal's position in the apparatus, regardless of the type of behavior we observed in that position.

The types of receptive fields we have measured for cells in the hippocampus range from a simple one with a single "on" arm to a complex one with alternating "on" and "off" arms. So far these receptive fields do not fall into any obvious categories as those of the visual system do. There are obvious differences among individual cells in terms of their overall rate of activity, the number and discreteness of their "on" and "off" arms and the magnitude of the change in the cell firing rate when the animal enters an arm, but grouping cells into categories based on these different response characteristics must await more extensive experimental information.

How does a place unit know where in space it should be active? O'Keefe and his colleagues have addressed this question by testing animals in a dimly lighted chamber with black walls. On each of the walls was displayed a single prominent stimulus: a light, a rotating fan, a loudspeaker emitting sound and a white card, all of which together activated the place unit. Removal of any one of the four stimuli had little effect on the cell's activity, presumably because the remaining three stimuli allowed successful orientation. When any three of the stimuli were removed, however, the cell's firing pattern became erratic and unpredictable. These findings suggest that place units receive information from a constellation of spatial stimuli in the environment rather than from just one stimulus. Thus each place unit recognizes a particular spatial location by "triangulating" among stimuli in different parts of the environment, much as a surveyor or a navigator determines his location in space by measuring the relative positions of fixed landmarks.

We have looked primarily at place units in our experiments, but other types of cells in the hippocampus have also been described. It is known from the work of Case H. Vanderwolf of the University of Western Ontario that when animals are engaged in voluntary behavior such as exploring and running, their hippocampus exhibits a rhythmi-



OSCILLOSCOPE TRACE shows the activity of a single cell in the hippocampus as the rat runs freely in the radial-arm maze. The cell's activity, which was recorded by means of an implanted metal electrode, is strikingly correlated with the rat's position in space. Cell's firing rate is slow when animal starts on Arm 5, speeds up on arms 2 and 3, slows down on other arms and increases again on Arm 3.

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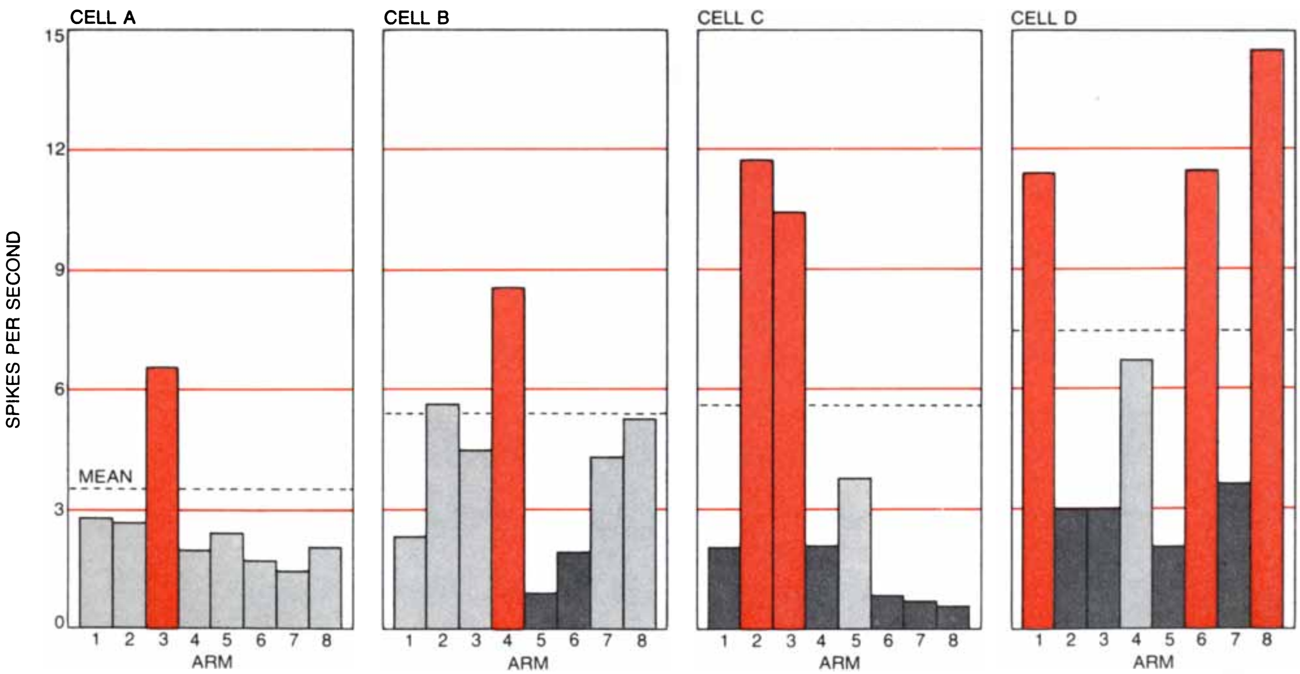
cally varying electric potential known as the theta rhythm. Ranck identified a group of cells in the hippocampus whose activity is strongly correlated with this rhythm. O'Keefe and Black subsequently found that when they trained rats to jump from the floor of a cage to a small ledge, and then varied the distance between the floor and the ledge, the frequency of the rhythmic firing of these cells was related to the distance the animal had to jump in order to reach the ledge. When they placed small weights on the animal's back to vary the amount of force required to make a jump, the activity of the cells did not change, indicating that the distance of the jump was the critical variable. O'Keefe accordingly named the rhythmically firing cells "displace units," since their activity depended on the distance the animal was about to move. Hence it appears that the hippocampus has at least two classes of cells: place units that reflect where the animal is at the present time and displace units that reflect the distance it is about to move in the environment.

In sum, our experiments with brain lesions and those with nerve-cell recordings suggest that the hippocampus plays an important role in spatial working memory and provide support for O'Keefe and Nadel's spatial-map hypothesis as well. Without the hippocampus the ability of rats to perform the radial-maze task correctly is severely impaired. With the hippocampus intact the rats do well, and the activity of nerve cells within the hippocampus is strongly correlated with the animals' position in space.

As with many experiments, the information we have obtained now raises an entirely new set of questions. Some of them have to do with the performance of normal animals. Why did the rats not adopt any of the strategies that might have made the task easier for them? Was it because of a limitation of rodent cognitive processes or the task's being so simple that it did not provide a sufficient challenge? Other questions have to do with the physiological bases of spatial working memory. Our results suggest an important role for the hippocampus, but the late Hans-Lukas Teuber of M.I.T. and Brenda A. Milner of the Montreal Neurological Institute have suggested that other parts of the brain, such as the parietal lobe, may be involved in spatial memory, at least in man. What are the factors responsible for this apparent discrepancy between the brain mechanisms of spatial behavior in human beings and in rodents?

Future research must also consider the way in which the cellular organization of the hippocampus enables it to store and retrieve spatial information. Per Andersen of the University of Oslo has demonstrated that the hippocampus contains many small and complex circuits, and Leonard E. Jarrard of Washington and Lee University is currently examining their function by making discrete lesions in the hippocampus that selectively disrupt particular circuits. He has found that lesions in different circuits have markedly different behavioral effects. For example, a particular lesion appears to disrupt the acquisition of spatial memory but not its retention. These results suggest that a more subtle level of anatomical and functional analysis must be pursued if we are to understand the role of the hippocampus in the programming of spatial memory.

One tantalizing piece of anatomical evidence relating to the idea of the hippocampus as a memory system is the organization of the synaptic connections linking the hippocampus to the fornix and to the entorhinal area. The connections distribute themselves in a regular manner from the front of the hippocampus to the back, and the pathways that make the connections run at right angles to other pathways within the hippocampus so as to form an extensive and highly structured network. This arrangement of nerve fibers has reminded many people of the wires running at right angles to one another in the core memory of a computer, where a "bit" of information can be stored at each intersection of the wires. Although it is unlikely that the hippocampal system stores information the same way, its structural resemblance to a computer memory raises still other questions about the memory mechanisms of the brain.



SPATIAL STIMULI that excite or inhibit the firing of four prototypical cells in the rat hippocampus are shown graphically. Each set of bars represents the eight arms of the radial-arm maze. An arm is classified as being "on" (*color*) for a given cell if, when the animal enters that arm, the cell's firing rate increases by at least three standard errors of the mean away from the overall mean rate. An "off" arm (*dark gray*) must consistently produce a decrease in firing rate of the same magnitude. Arms in neither category are considered neutral (*light gray*). The responses of individual cells in the hippocampus to spatial position vary greatly. Cell *A* has a very simple response pattern with a single "on" arm. Cell *D*, however, has a complex pattern with alternating "on" and "off" arms. *B* and *C* are in between.

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The Lesson of Retrolental Fibroplasia

This type of blindness was epidemic among premature infants in the 1950's. How the problem was solved by trial and error is a parable of the issues that arise in medical experimentation on human beings

by William A. Silverman

The form of blindness known as retrolental fibroplasia arose abruptly in the early 1940's among infants, most of whom had been born prematurely, and quickly became an epidemic. It is an irony of medicine that the disease stemmed from the efforts of physicians to increase the premature baby's chances of survival in good health. After some 12 years of intensive and widespread investigation the cause was found and the disease was virtually eradicated. The entire episode bears recall now because it presents so sharply the painful questions that surround experimentation with human beings, particularly newborn infants.

The story of retrolental fibroplasia can be told within the framework of the French physiologist Claude Bernard's description of the stages of development of experimental knowledge: "In all experimental knowledge there are three phases, an observation made, a comparison established and a judgment rendered." Here the first phase began on February 14, 1941, when Stewart H. Clifford, a Boston pediatrician, made a routine home visit to examine a baby girl who had been born prematurely three months earlier. "Although the baby's general development was excellent," Clifford recalled recently, "I was shocked to note roving nystagmus [jerking movements of the eyeballs] and opacities in the eyes. I had to tell the family I was afraid the baby could not see. I immediately referred the baby to one of our leading ophthalmologists, Paul A. Chandler."

Chandler examined the infant's eyes and told Clifford he had never seen anything like them before. He had the baby admitted to a hospital, where her eyes could be examined while she was under anesthesia, and consulted with Frederick H. Verhoeff, a leading figure in American ophthalmic pathology. The examination revealed a heavily vascularized grayish membrane, which appeared to be on the rear surface of each lens. The problem was diagnosed as a fibrovascular sheath of the lens. An operation was considered but dismissed, since Verhoeff thought the prognosis was poor.

Within a week Clifford saw his second case of the disorder when he was called to examine a baby boy who was the survivor of twins born prematurely in July, 1940. (The baby's twin sister had died within a few hours of birth.) Clifford called in Theodore L. Terry, a Boston ophthalmologist, who declared that the condition was congenital cataracts. He arranged for the baby to be admitted to a hospital for an operation, but shortly before the operation was scheduled to begin Clifford, Chandler and Verhoeff, who were present as consultants, convinced him that the condition was inoperable.

The nursery records of these first two children were recently reviewed. They showed that each infant had been given the standard treatment of the time for premature babies, which included incubation in an environment enriched in oxygen. It was evident from the records that the disorder seen by Clifford in their eyes was what later came to be known as retrolental fibroplasia, from the Latin for formation of fibrous tissue behind the lens. (The term was coined by Harry Messenger, a Boston ophthalmologist who, as Chandler put it, was "quite a Latin and Greek scholar and who was often called on to provide a suitable name for various things.")

It soon became apparent that the disease was widespread. In 1942 Terry published in *The American Journal of Ophthalmology* a note on five cases he knew of. The note included two prophetic sentences: "In view of these findings [that all five children had been born prematurely] perhaps this complication should be expected in a certain percentage of premature infants. If so, some new factor has arisen in extreme prematurity to produce such a condition."

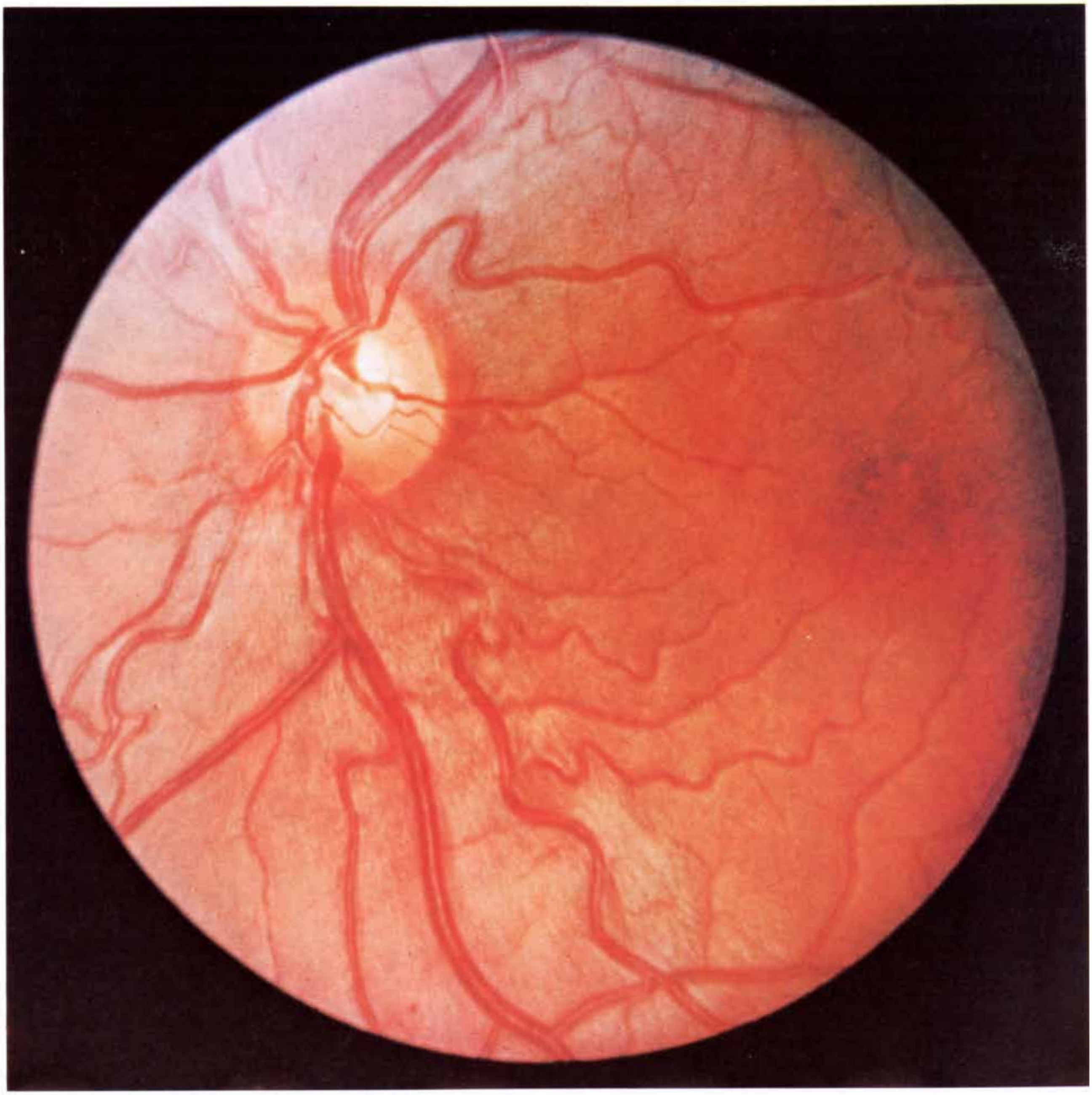
Between 1942 and 1945 Terry collected data on 117 cases of the disorder. Only eight of the cases were in infants said to have been born following a pregnancy of normal length. Terry became convinced that the condition developed after birth, because in three premature infants whose eyes were normal at birth he subsequently found well-established retrolental fibroplasia. Notwithstanding his view, the notion persisted until 1948 that the condition resulted from an inherent or acquired abnormality of the eye due to factors operating before birth or, at the latest, immediately after birth.

In 1948 two ophthalmologists at the Johns Hopkins Hospital (William C. Owens and Ella U. Owens) examined more than 200 premature infants at birth. None of them had retrolental fibroplasia. Half of the babies were reexamined monthly until they were six months old; by then 4 percent had developed the disease. The survey showed that the first detectable abnormalities began from two and a half to three and a half months after birth and involved a progression of changes in the blood vessels of the retina. The findings were quickly confirmed, and it soon became routine in large research centers studying the disorder to make ophthalmoscopic examinations of the eyes of all premature infants at weekly intervals in the hope of diagnosing retrolental fibroplasia early.

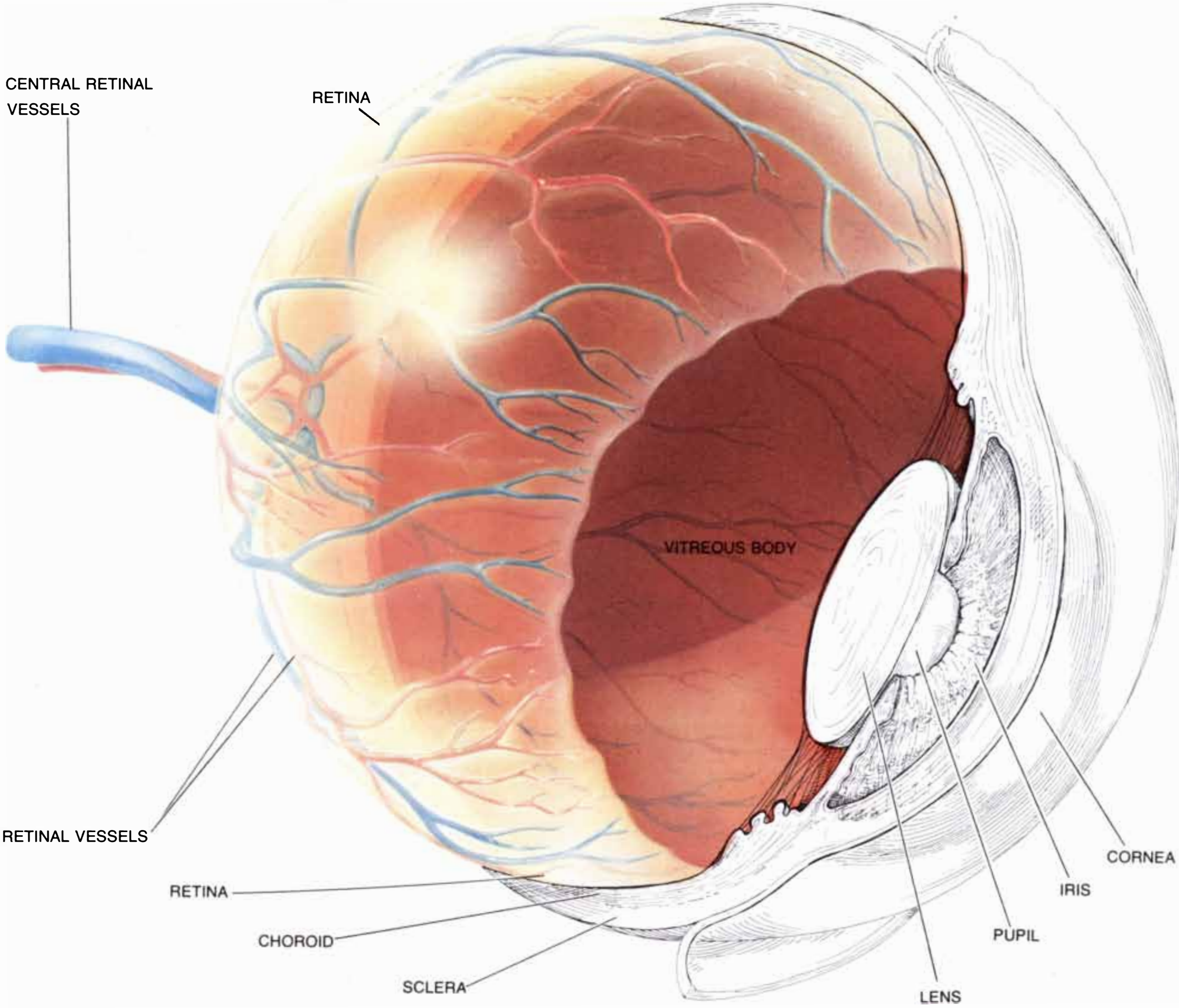
During those years I was in the department of pediatrics at the Columbia University College of Physicians and Surgeons and also on the staff of Babies Hospital of the Columbia-Presbyterian Medical Center. A case of retrolental fibroplasia in a prematurely born infant we cared for in 1950 is illustrative of the anecdotal and uncontrolled approach that has characterized much clinical research. On the day after the detection of the early signs of the illness I wrote on the baby's chart: "It is clear that any measures undertaken to influence the course of the disease must begin now. It must also be mentioned that at least one instance has been recorded (Owens and Owens) where these changes of ... the retina [abnormal twisting of veins and unusual conspicuousness of blood vessels] have apparently failed to go on to the fibroplastic retrolental membrane stage and reverted to normal. This admittedly is a very remote possibility, but the fact that it has been observed will make interpretation of the beneficial effect of any therapeutic measure just that uncertain.... It has been decided to try ACTH [adrenocorticotrophic hormone] on the rationale that (1) it is a connective-tissue disease, (2) prematures may be ACTH-deficient and (3) no other agent or therapeutic regime has given any indication of beneficial effect."

The previously untried treatment was begun. The vascular changes in the eyes improved, and so the dose was lowered. The changes became worse, whereupon the dose was increased. The eyes returned almost to normal, and ACTH was withdrawn. The infant gained weight and was sent home.

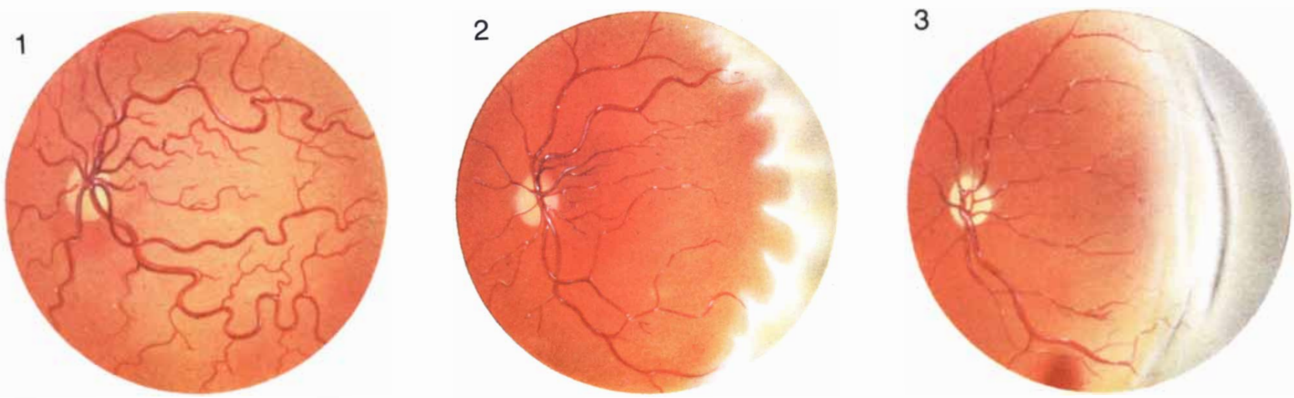
Soon after this dramatic experience 31 infants with the early changes of retrolental fibroplasia were treated with ACTH at Babies Hospital. Permission for this innovative approach was ob-



VIEW OF RETINA through a direct ophthalmoscope shows blood-vessel abnormalities characteristic of retrolental fibroplasia, notably the hairpin bends in many of the arteries. In the normal retina the arteries are nearly straight. This photograph shows the retina of a teenage child who was born prematurely and became afflicted with retrolental fibroplasia as a result of the oxygen-rich environment that was then standard treatment for premature infants. The affliction did not lead to impairment of vision, but the arterial changes persist.



NORMAL HUMAN EYE is depicted in a view that shows structure of the blood vessels of the retina. Arteries are portrayed in red, veins in blue. The retina extends around the eyeball inside the choroid and the sclera. Much of the center of the eyeball is filled with the clear structure known as the vitreous body. In the normal eye the retinal blood vessels do not leave the retina, but in the wild and twisting growth associated with retrolental fibroplasia the capillaries may frequently break through the retina and penetrate the vitreous body.



DEVELOPMENT OF RETROLENTAL FIBROPLASIA is traced in a series of drawings based on what was seen through a direct ophthalmoscope. The drawings show part of the background of the left eye of a prematurely born infant at the age of five weeks (*1*), nine weeks (*2*) and 11 weeks (*3*). In the first drawing the retinal blood vessels are severely dilated and twisted. At nine weeks a crescent-shaped swelling of the retina has begun to form at the right outer edge of the field and the retina has started to detach. In the final drawing the detachment of the retina has progressed to the stage where a fold, which is shown by curving line near right edge, has developed in the retina.

tained from the parents in the same informal way that it had been a few years earlier when another "miracle" drug, penicillin, was employed to treat life-threatening infections of various kinds. Of the 31 infants, 25 left the hospital with normal eyes, two became blind, two lost all vision in one eye and two had useful vision with only minor retinal scars.

These results were particularly impressive compared with those of seven infants with early retrolental fibroplasia at Lincoln Hospital in New York who did not receive ACTH because its efficacy had not been proved. Six of them became blind. ACTH seemed to be the cure for the disease.

We were puzzled, however, by two infants (one from Lincoln Hospital and one from another New York hospital) whose early changes subsided without treatment and who were left with normal eyes. It seemed clear that only a randomized and concurrently controlled trial (in which one group of patients continues to receive the standard treatment and one receives the proposed new treatment, with a patient being allocated to one group or the other strictly at random) would settle the question of the effectiveness of ACTH.

The trial was made. About a third of the infants who received ACTH became blind, whereas only a fifth of the control infants did. Moreover, there were more deaths in the ACTH group. Two years later William Owens published the observation that approximately three-fourths of the infants showing the early changes of retrolental fibroplasia returned spontaneously to normal. This was exactly our experience in New York during the treatment with ACTH.

More than 50 separate causes of retrolental fibroplasia were proposed. About half of them were examined formally; only four were tested by prospective experimental clinical trials. Gradually, as the clinical evidence accumulated, attention was focused on the oxygen-rich environment routinely provided for premature babies as a factor in the causation of retrolental fibroplasia. Significantly, as one looks back, a question that was hotly debated in the early 1950's was whether the causative factor was an excess of oxygen or a lack of oxygen in the baby's retinas. Two physicians, Kate Campbell in Australia and Mary Crosse in England, who have been credited with discovering the cause of the disease, published anecdotal evidence incriminating an excess of oxygen in observations made in a population of 142 infants. In Paris the opinion (based on observations of 479 infants) was the reverse. Charity Hospital in New Orleans, which had the largest premature-baby unit in the U.S., was free of retrolental fibroplasia notwithstanding the routine continuous administration of oxygen.

Norman Ashton of the Institute of Ophthalmology of the University of London advanced a hypothesis that the disease entailed an abnormal overgrowth of the developing blood vessels of the retina. There was indirect evidence suggesting that the normal stimulus attracting blood vessels into the fetal retina is an oxygen demand arising in the inner layers of that part of the eye in the fourth month of gestation. This view came from the work of the Israeli ophthalmologist I. C. Michaelson on the development of the retina in several species, including man.

Michaelson had injected India ink into the arterial system of the eye of human fetuses at autopsy and then teased the retina out to make flat preparations. One of his principal findings was that the capillaries bud from the veins, away from the oxygen-laden arteries, leaving a zone free of capillaries. Later work showed that when animals were reared at a simulated high altitude, in an atmosphere with a reduced oxygen content, the capillary-free zone became narrower. Although the relevance of these observations to retrolental fibroplasia went virtually unnoticed for several years, the findings supported Ashton's later hypothesis that the disease was caused primarily by a severe lack of oxygen in the deep retinal layers of the developing eye.

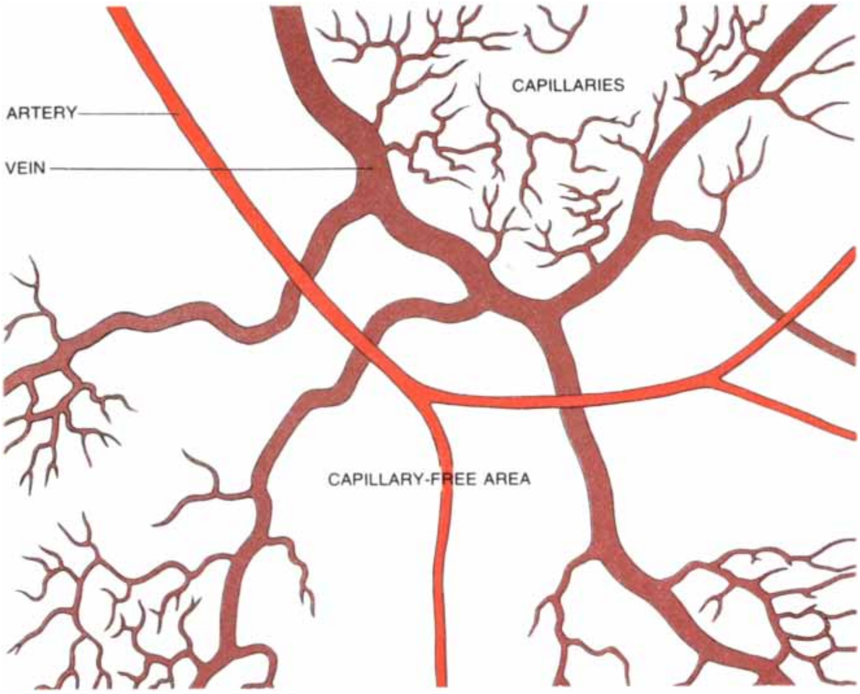
Ashton came to the problem armed with the knowledge that the newborn kitten had an incompletely vascularized retina, roughly comparable to the retina of the human infant at about the seventh month of gestation. Ashton and his coworkers put a cat and three kittens in an atmosphere enriched in oxygen. The first experiment showed that after four days of continuous exposure to an atmosphere that contained from 75 to 80 percent oxygen the outgrowing blood vessels of the retina were completely attenuated. The initial effect of the oxygen was shown to be a marked narrowing of the immature retinal vessels, followed by their obliteration. Paradoxically it was exposure to the high level of oxygen, with the resulting eradication of germinating blood vessels, that appeared to cause the ultimate deficit of oxygen in the deep retinal tissues of the eye. After the kittens had been returned to a normal atmosphere the blood vessels grew in a disorganized fashion, with a budding of new capillaries out of the normal retinal area into the vitreous body.

At Gallinger Municipal Hospital in Washington, D.C., Arnall Patz, a resident in ophthalmology, designed a test in which some premature babies in incubators would be given less supplemental oxygen than was the standard at the time. The study turned out to be a difficult trial for the investigators. As Patz recalls it: "The nurses were convinced that we were going to kill the babies in the low-oxygen group; at night some of the older nurses would turn the oxygen on for a baby who was not receiving oxygen and then would turn it off when they went off duty in the morning." Although the test, involving 76 infants, appeared to incriminate high levels of oxygen in the causation of retrolental fibroplasia, the debate over oxygen continued.

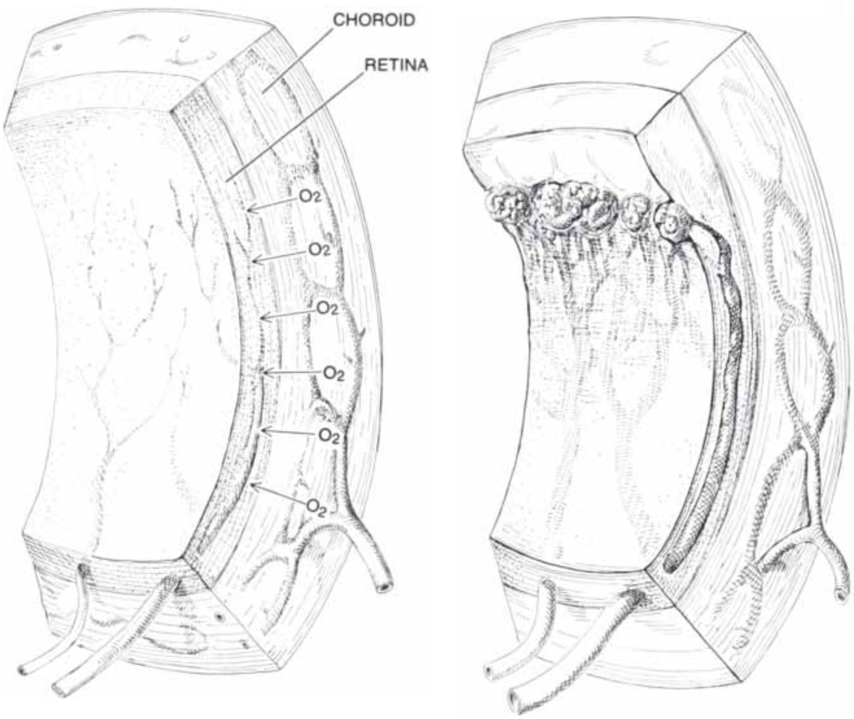
Early in 1953 the oxygen issue was discussed at a meeting called for the purpose at the National Institutes of Health. Two strong views emerged. A majority thought that a formal, controlled trial should be carried out simultaneously in several medical centers. A minority, arguing that there was already enough observational evidence to indict oxygen, opposed the trial as immoral. The dispute reflected a basic problem in medicine, which Bernard had described 100 years earlier: "Many physicians attack experimentation on human beings, believing that medicine should be a science of observation, but physicians make therapeutic experiments daily on their patients, so this inconsistency cannot stand careful thought. Medicine by its nature is an experimental science but must apply the experimental method systematically." Briefly, the majority thought the participants who opposed the need for formal and controlled experiments were in effect asking for the substitution of informal and uncontrolled experiments.

The study began in July, 1953. Over a period of a year nearly 800 infants in 18 hospitals were studied. They had in common the fact that they were born prematurely and that each one weighed 1.5 kilograms or less at birth. During the first three months enrollment was in random sets of three. Two infants in each set were allotted to a group that received supplemental oxygen only when clinical indications called for it, and then in a concentration of no more than 50 percent; the third infant received what was at that time the routine treatment of being given oxygen continuously at a concentration of more than 50 percent for 28 days. For the remaining nine months of the trial all the infants were given curtailed oxygen only.

The results were dramatic. Retrolental fibroplasia occurred in 23 percent of the infants in the routine-oxygen group and in 7 percent of the group that received oxygen in curtailed amounts. (This last finding is a seldom remembered detail of the trial and deserves emphasis. Not every infant receiving "curtailed" oxygen by the standards of the



BLOOD-VESSEL DEVELOPMENT in the retina was examined by the Israeli ophthalmologist I. C. Michaelson, who found that in normal conditions the capillaries bud out from the veins and tend to stay clear of areas around arteries. When experimental animals were reared in an environment low in oxygen, the capillary-free zone became narrower. The findings supported a hypothesis that oxygen demand in the retina caused blood vessels to proliferate and that therefore a lack of oxygen was cause of retrolental fibroplasia. Later it was shown that retinal oxygen deficit was in fact caused by prolonged breathing of oxygen at high concentration.



EFFECT OF OXYGEN on the infant retina is at first (*left*) to cause the developing blood vessels to constrict and then to wither and become obliterated. The arrows indicate increased diffusion of oxygen from blood vessels of the neighboring choroidal layer; these channels are not appreciably affected. Later the withered blood vessels of the retina regrow in a disorganized fashion (*right*), erupting through the retinal surface into the vitreous body. These effects appear only in incompletely developed retinas, which is why retrolental fibroplasia afflicted mostly prematurely born infants who had been exposed to high levels of oxygen in incubators for days.

time escaped the disease.) The study also showed that the risk of the disease increased with each day in an oxygen concentration of more than 50 percent for up to two weeks of exposure; thereafter it leveled off.

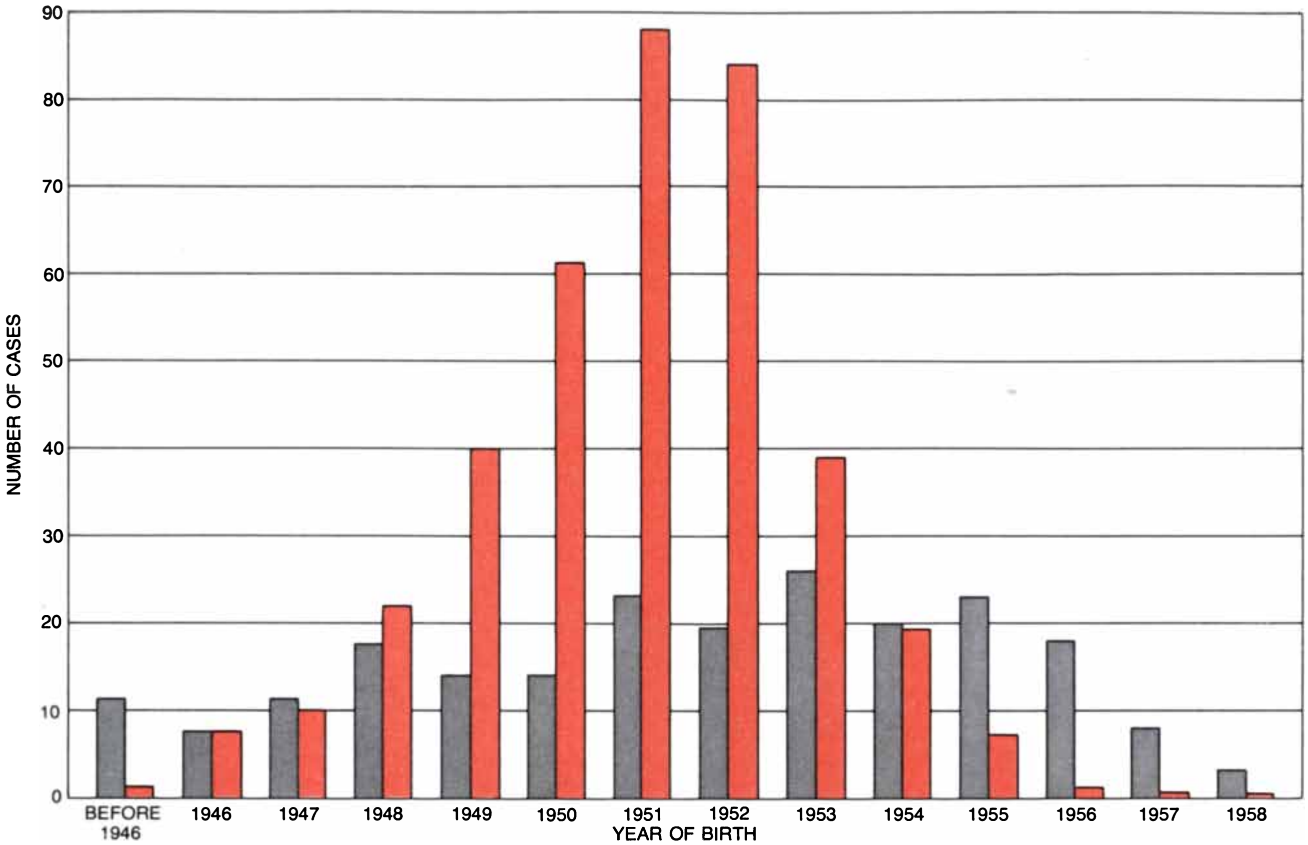
The study and its results represented the second and third stages mentioned by Bernard, "a comparison established and a judgment rendered." The results were announced at the annual meeting of the American Academy of Ophthalmology and Otolaryngology in 1954. The announcement was immediately and widely publicized. Within a year the practice of giving premature infants a high concentration of oxygen was widely modified. The disease subsided as quickly as it had arisen.

By now it was apparent that the reason for the sudden appearance of the disease was related to the general acceptance of a hypothesis (put forward in the early 1940's) that the high toll of brain damage in premature infants was caused by a lack of oxygen that up to then had not been recognized. This view provided the rationale for the continuous administration of a high concentration of oxygen, even to babies who showed no abnormal symptoms. At the end of World War II incubators were designed and built to meet the new specifications of physicians for providing high concentrations of oxygen.

Oxygen at high concentrations can be toxic, as it proved to be to the developing blood vessels of the retina of the premature infant. The result in retrolental fibroplasia was that the developing retinal vessels withered. Subsequently there was a wild regrowth of the vessels. Although this proliferative process usually subsided, leaving a normal retina, in a small number of cases extensive hemorrhages developed and fibrous scar tissue formed, causing the retina to become detached from its normal position and to billow out against the back of the lens.

Medically the story appeared to be complete, and interest in the disorder quickly waned as it became one of the rarer complications of premature birth. Actually many of the challenges of the experience with retrolental fibroplasia had not yet been confronted. Now, more than 20 years later, several crucial questions remain.

The first sign of trouble began five years after the cooperative study. Mary Ellen Avery and Ella H. Oppenheimer of the Johns Hopkins School of Medicine reported that the frequency of death from hyaline membrane disease was higher in infants at the university hospital than it had been during a five-year period before 1954, when oxygen was administered liberally to premature babies. In 1963 Alison D. McDonald of



RISE AND DECLINE of retrolental fibroplasia is reflected in this chart of blindness among children in southern California. The chart shows the number of cases of blindness attributable to retrolental fibroplasia (*color*) and to other causes (*gray*). Eventually the abrupt appearance of retrolental fibroplasia was traced to the adoption of a policy of liberal administration of oxygen to prevent brain damage in premature infants. The brain damage is caused by a lack of oxygen that is difficult to recognize. At the end of World War II incubators were designed to make it technically feasible to administer a high concentration of oxygen continuously to a premature infant.

Guy's Hospital in London reported the experience of 19 centers for the newborn in England and Wales before and after the restricted use of oxygen. She found that with increased treatment with oxygen the frequency of retrolental fibroplasia rose but the incidence of spastic diplegia (palsied lower extremities) fell.

Kenneth W. Cross of the London Hospital Medical College recently examined the trend in the death rate of newborn infants in England and Wales over the past 40 years. He found a smooth exponential decrease in the rate of death during days one to six after birth, but the curve for the rate of death on the day of birth (day zero) showed a skewed break in the downward trend, particularly in infants whose weight was low at birth. The same anomaly appeared in data from the U.S. The break corresponded closely with the beginning of restrictions on oxygen therapy for infants.

Cross estimated the number of excess deaths per year following the adoption of the restrictive policy by subtracting the number of deaths that were expected (a figure obtained by extrapolating the smooth curve preceding the reduction in oxygen therapy) from the number of deaths that had occurred. The excess amounted to about 700 per year. Dividing this figure by a number representing the decline in blindness from retrolental fibroplasia, Cross calculated that 16 deaths occurred to produce each sighted infant during the years of oxygen restriction. (The study did not take into account the fact that the break in the curve also coincided with the introduction of certain medicines to prevent and treat infection; these substances were later shown to be dangerous to premature infants.)

One may ask why the cooperative study in the U.S. failed to discover the risk that curtailed oxygen therapy might increase the death rate in certain infants. This disturbing oversight is related to a deliberate quirk in the original design of the study. Infants were not enrolled in the trial until they had survived for 48 hours. The reason was that most of the deaths among premature infants are in the first two days of life; it was argued that the inclusion of these early deaths would not help to answer the question of oxygen damage to the retinal blood vessels. The strategy also had the advantage of placating the nurses, most of whom were extremely resistant to the policy of restricting oxygen. It was some time before a balance was struck (which is not yet an ideal one) whereby premature infants who need extra oxygen to survive without brain damage receive it, but in concentrations that do not seem to be giving rise to blindness.

The success of the effort to solve the puzzle of retrolental fibroplasia had a good deal to do with the large expansion by Congress of appropriations for medical research beginning in the late 1950's. Much of the research was directed at problems affecting the fetus and the newborn infant, with fruitful results for both biology and medicine. Notwithstanding the advances in every branch of medicine, which have taken the profession out of the age of magic for the first time, one sees a widespread erosion of public confidence in the medical profession.

Perinatal medicine, which is directed at disorders of the infant during the period shortly before and shortly after birth, provides an example. The nature of the problem, as it has been stated by Howard Brody of Michigan State University, is that "scientists or clinicians are prone to error when they confuse scientific problems with value problems and try to solve the latter with tools of the former." As knowledge of perinatal disorders has deepened, physicians have too often come out of the laboratory advising treatments that have been neither fully tested nor presented to the community for consideration and approval. However noble the objectives of these physicians may appear to be, both the practice and the science of perinatal medicine have been handicapped.

The philosopher Kurt von Fritz notes that "there are no absolute criteria by which a value system of a society can be judged objectively." I go further: There are no absolute criteria by which the values of an individual can be judged with complete objectivity. As a result the evaluation of risk versus benefit in all medical interventions (whether they are proved or experimental) is a difficult and individualized process, particularly in the pluralistic society of the U.S.

The late Henry K. Beecher of the Harvard Medical School classified all experiments on human beings into groups that have been summarized in two mutually exclusive categories: therapeutic and nontherapeutic. His basis for classification was the intent of the experimenter, not the risk. This classification has been accepted uncritically by almost everyone.

The scientific view of the world, however, is probabilistic: risk and benefit are relative, not absolute. They should be evaluated in what could be called a systems view, in which categories of risk and benefit would be weighted. The heaviest weight usually would be assigned to the risk and benefit affecting the individual (or the mother-baby unit while the infant is still a suckling), with progressively less weight being given to the family, the community, the subculture and so on.

Indeed, the current debate about informed consent for experimentation on the fetus and the newborn infant is pointless. Interpretations of risk versus benefit and the social status of these individuals are value judgments that will be decided differently by different subcultures in the society. To impose one solution on everyone is immoral.

The situation now is that the Federal Government has imposed restrictions on "nontherapeutic" research affecting the human fetus and suckling infants. In my view this is a sorry state of

ADVANCED STAGE of retrolental fibroplasia appears in this photograph of a horizontal cross section of an eye. The lens is the oval structure at the left, and the gray mass next to it is the retina, which has become completely detached. Retrolental fibroplasia was originally thought to be a lens disease because of the gray fibrous tissue found behind lens in severe cases.

affairs. The profusion of new drugs, the advances in medical practice and the concern over the effects of environmental factors on health have made this a time when more rather than less experimentation involving human beings, including children, is needed. The experiments should be scrupulously designed and carefully surrounded with safeguards. Unfortunately those conditions are not always observed in modern experiments, which are frequently not even acknowledged to be experiments. Regrettably the medical profession had a role in creating the situation.

In 1967 a state senator in New York attracted wide public attention with the assertion that barbarous experiments on children were being conducted in the municipal hospitals of New York City. He drafted legislation to outlaw all experimentation on children. The medical profession responded with a proposal for legislation that would allow carefully safeguarded clinical investigation involving children. The senator abandoned his attack, apparently because it was no longer exciting public interest, and the medical profession thereupon dropped the subject too. Subsequent events, which culminated in the current restrictions, indicate how wrong it was not to pursue the matter in a more responsible way at the time.

The threat in 1967 had the effect of encouraging bootleg studies, that is, experiments that are neither formal nor informal and so avoid the issues of informed consent and strict review. By the simple device of labeling innovative treatments as "not experimental" but merely "modification or evolution of existing practice" and "based on sound physiologic principles," investigators have proceeded to apply new therapy. The rules of evidence for scientific investigation are ignored in these anecdotal trials.

Thus the trial-and-error approach that led to the retrolental fibroplasia episode is being repeated on a wide scale. This Russian-roulette strategy of empirical studies is condoned and even widely praised, whereas efforts to test new treatments with randomized, controlled clinical trials that limit risk are characterized as "daring." A recent comment by an academic physician described the controlled-trial method as "always comforting" but "probably not a very effective way to assess therapy that may be dependent on a number of variables." In the present situation of ill-conceived restrictions and bootleg experiments it is as if more than 10,000 children had not been blinded by retrolental fibroplasia, Bernard's words had never been spoken, R. A. Fisher had never developed the randomization approach to the problem of multiple variables and A. Bradford Hill had never perfected the format for controlled clinical trials.

Lectins

These proteins found primarily in plants combine specifically with sugars on cell surfaces and hence bind cells together. They are key tools in the study of the role the cell surface plays in cell behavior

by Nathan Sharon

The social behavior of the living cell—including intercellular communication, the regulation of cell growth and differentiation, the immune response and perhaps malignancy—is mediated primarily by the surface of the cell, and more particularly by the branching sugar molecules that stud the cell surface. Our recent recognition that this is so and our increasing understanding of the architecture and function of the cell surface are due in large part to a class of proteins called lectins, which bind to sugar molecules much as enzymes combine with their substrates and antibodies combine with their antigens.

Some of the lipid (fat) molecules and proteins that comprise the cell's outer membrane carry branching chains of sugar molecules (oligosaccharides, or, more briefly, saccharides) that extend from the cell surface: they are glycolipids and glycoproteins [see "Glycoproteins," by Nathan Sharon; SCIENTIFIC AMERICAN, May, 1974]. When lectins, which have multiple combining sites, bind to these saccharides, they interconnect large numbers of cells, causing them to agglutinate, or clump together. Particular lectins bind more or less specifically to particular sugar molecules or groups of molecules. (It was for this property of selectivity that lectins were named in 1954 by one of the pioneers in the field, William C. Boyd of the Boston University School of Medicine, from the Latin *legere,* to pick or choose.)

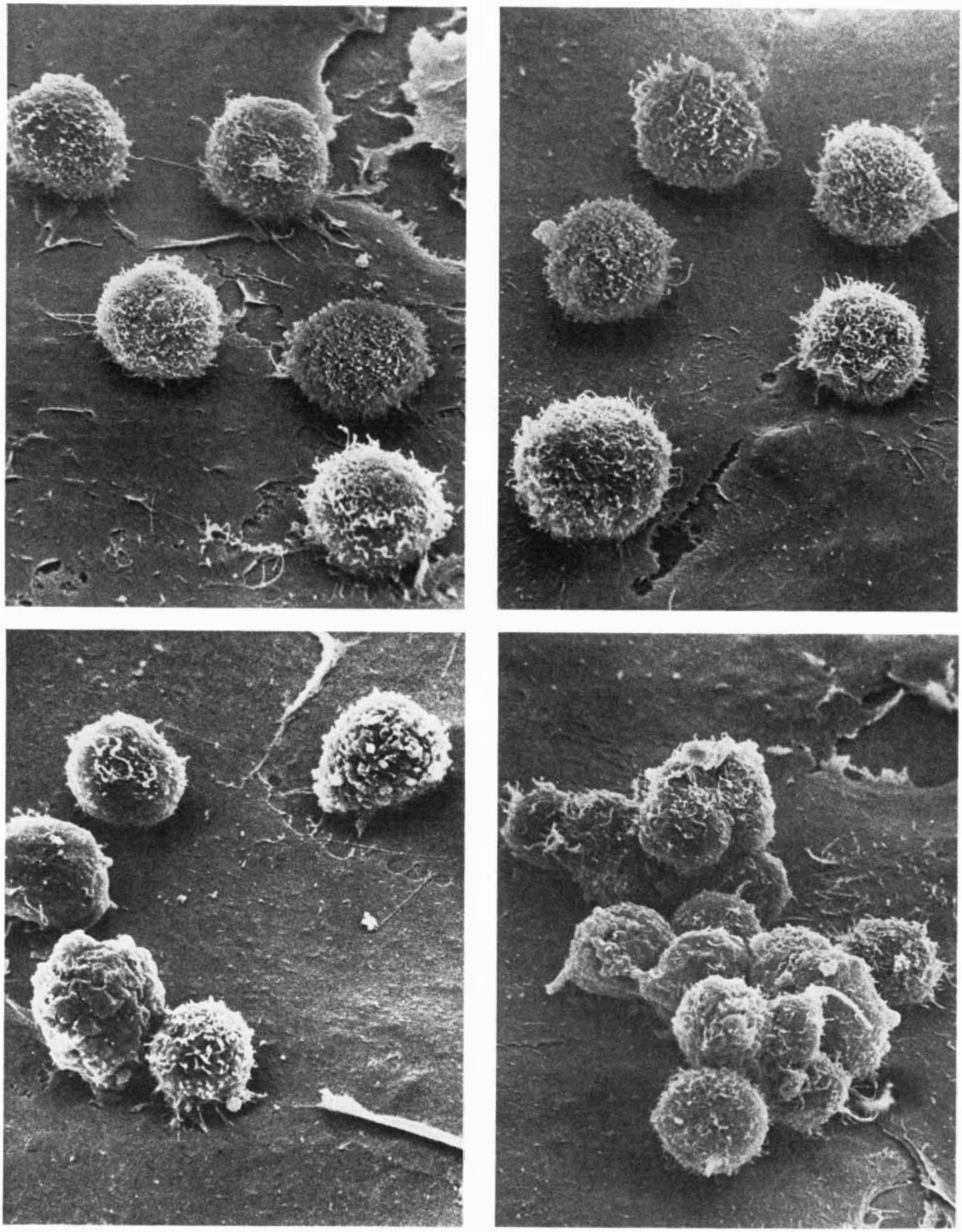
Because the agglutination response is selective, lectins are valuable as probes for identifying and mapping the sugars on the surface of cells. They can distinguish among the red blood cells of various blood groups, and because they readily agglutinate malignant cells they can often distinguish such cells from normal ones and reveal some of the changes cells undergo when they become malignant. In addition lectins stimulate the division of the immune-system cells known as lymphocytes. During this process of mitosis the lymphocyte nucleus gets bigger and the individual chromosomes become discrete structures, so that lectins are a major tool in chromosome analysis as well as in studies of a broad range of immunological phenomena.

Lectins were first noticed almost 90 years ago for their ability to clump red blood cells, and so they were called hemagglutinins; because they were first isolated from plants they came to be known as phytohemagglutinins. In time it was discovered that lectins agglutinate not only red cells but also other kinds of cells, including lymphocytes, fibroblasts (connective-tissue precursors), spermatozoa, bacteria and fungi. Moreover, it has become clear that lectins are present not only in plants (including bacteria) but also in some invertebrate animals such as snails and in some vertebrates; recently Vivian Teichberg in our department at the Weizmann Institute of Science in Israel discovered a lectin in the electric eel. Lectins are apparently most widely distributed in plants, however: they have been found in almost 1,000 plants of some 3,000 examined in recent years. The legumes are particularly rich in lectins, which account for as much as 1.5 to 3 percent of the protein content of the soybean and the jack bean, for example. To date some 50 lectins have been purified and chemically characterized, most of them from plants.

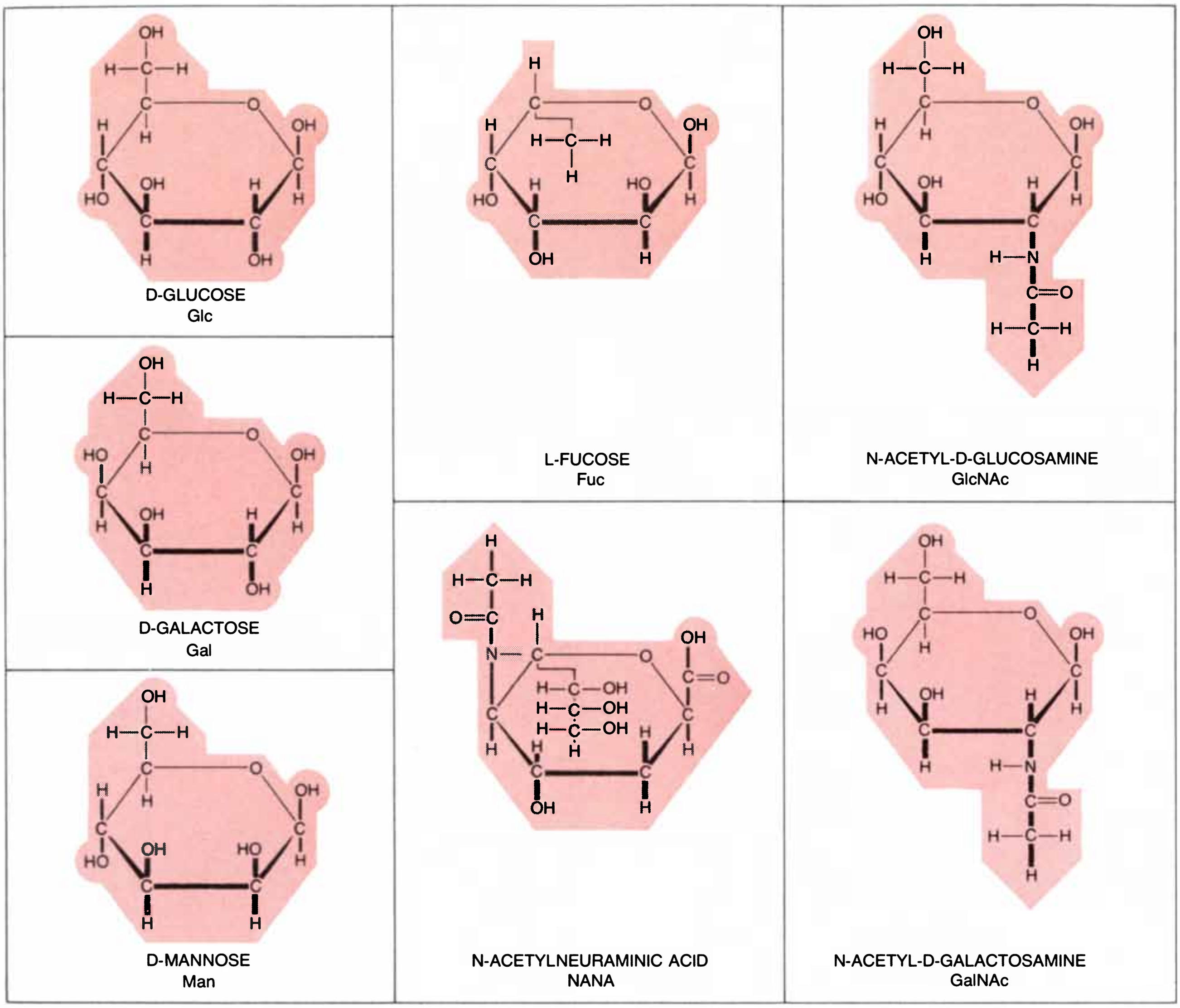
The first description of what we now know as a lectin was given by H. Stillmark in a report submitted in 1888 to the University of Dorpat in Estonia, one of the oldest universities in Czarist Russia. While investigating the toxic effects on blood of extracts of the castor bean (*Ricinus communis*) Stillmark observed that the red cells were being agglutinated. He obtained evidence that the material responsible for the agglutination was a protein and gave it the name ricin. Shortly afterward H. Hellin of the same university discovered that the toxic extract of the seed of *Abrus precatorius* also caused the red cells to clump together. The new agglutinin was named abrin. It and ricin immediately drew the attention of the German bacteriologist Paul Ehrlich, who recognized that he could investigate certain problems of immunology with them rather than with bacterial toxins, such as the toxin of diphtheria, which were popular among bacteriologists at the turn of the century.

With ricin and abrin Ehrlich discovered some of the most fundamental principles of immunology during the 1890's. For example, in 1891 he reported that mice were rendered immune to ricin by repeated subcutaneous injections of small doses of the toxin. Later he found that the serum of an immune mouse could neutralize the toxicity of ricin. The action was specific: the "antiricin" that developed in the serum of an animal immunized with ricin would not neutralize the toxic effects of abrin, and "anti-abrin" would not neutralize ricin. Ehrlich thus demonstrated that the phenomenon of immunospecificity is associated with the antiserum. In 1908 Karl Landsteiner of the Rockefeller Institute for Medical Research reported that lectins are species-specific. He found that whereas small amounts of the lentil lectin would agglutinate rabbit red cells, even high concentrations of that lectin had no effect on pigeon red cells.

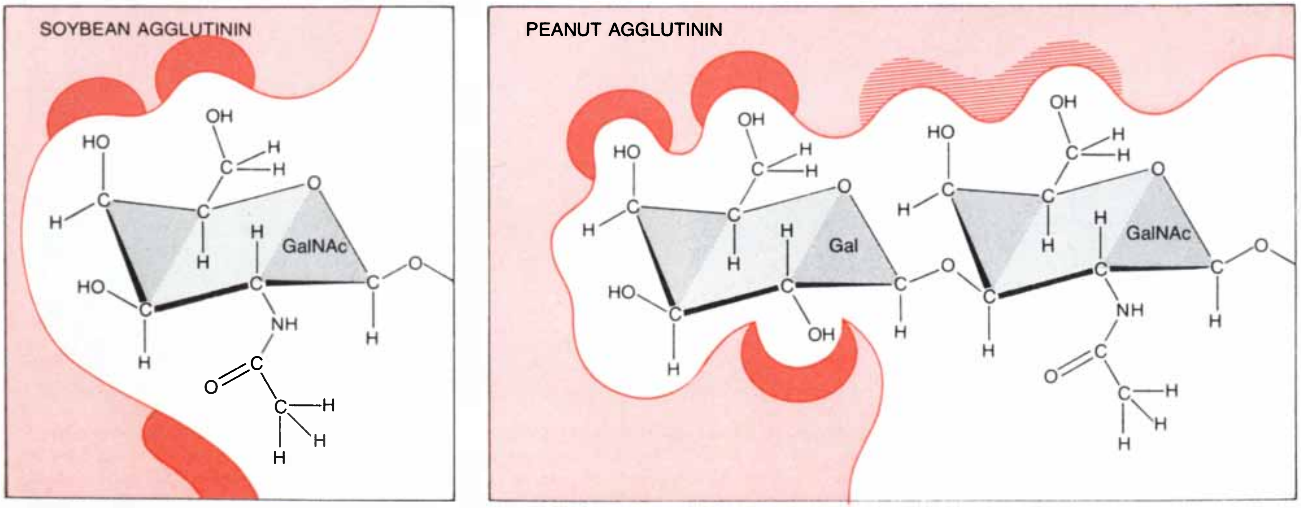
Most of the early experiments were conducted with plant extracts that were crude by present-day standards; it is now known that both ricin and abrin are mixtures of a highly toxic, sugar-binding but nonagglutinating protein and a lectin that is not toxic. The first lectin to be purified was concanavalin *A,* from the jack bean, which was crystallized in 1919 by James B. Sumner of Cornell University. (Its detailed three-dimensional structure has recently been established in the laboratory of Gerald M. Edelman of Rockefeller University.) In 1936 Sumner and Stacey F. Howell noted that the addition of concanavalin *A* to a solution of glycogen, the carbohydrate that acts as the storage form of sugars in organisms, would cause the glycogen to



EFFECT OF A LECTIN on normal cells and on malignantly transformed cells is contrasted in scanning electron micrographs made by J. G. Collard and J. H. M. Temmink of the Netherlands Cancer Institute. When normal mouse fibroblast cells (*top left*) are treated with the lectin concanavalin *A*, isolated from the jack bean, the cells are not agglutinated (*top right*). Fibroblasts (*bottom left*) that have been transformed by exposure to simian virus 40 (SV40), a virus that is carcinogenic in certain animals, are seen to behave differently: when the malignantly transformed cells are treated with concanavalin *A*, they agglutinate (*bottom right*). Cells are enlarged 1,800 diameters.



SIX MONOSACCHARIDES, or individual sugar units, commonly found in animal-cell surface membranes are diagrammed schematically along with glucose, from which all six sugars can be synthesized by the organism. Their central structure is the five-carbon pyranose ring, to which hydroxyl (OH) and other groups are attached. *D* and *L* indicate the spatial orientations of the groups attached to the ring.



BINDING SITES on lectins are thought to be clefts or grooves into which particular sugars fit, with certain side groups of the sugar making contact with small combining regions (*dark color*) on the lectin. Soybean agglutinin binds to acetylgalactosamine, perhaps as suggested at the left, or to galactose. Peanut agglutinin also binds to galactose, but it binds more firmly to a combination of galactose and acetylgalactosamine units, indicating that its binding site may have additional combining regions (*hatched areas*), as suggested at the right.

precipitate from the solution, and that the agglutination of red blood cells by concanavalin *A* was inhibited by cane sugar.

Sumner and Howell suggested that hemagglutination by concanavalin *A* might be the consequence of a reaction of the protein with carbohydrates on the surface of the red cells. Their early insight was supported by the finding in 1952, by Winifred Watkins and Walter Morgan of the Lister Institute in London, that hemagglutination by lectins could be inhibited or prevented by the addition of certain simple sugars. Apparently the inhibitory sugar molecules occupy combining sites on the lectins, interfering with the attachment of the lectin to sugar units on the red blood cells. In other words, lectins bind sugars, and they agglutinate red blood cells by means of that binding. For example, the agglutination of red blood cells by concanavalin *A* is inhibited specifically by the sugars mannose or glucose, indicating that concanavalin *A* binds mannose and glucose.

In 1945 Boyd had discovered that a lectin can be "blood-group specific," that is, it will agglutinate red blood cells of one type but not those of another type. Boyd found that lima bean lectin would agglutinate red cells of human blood type *A* but not those of type *B* or type *O*. A little later K. O. Renkonen of Helsinki reported that the seeds of *Lotus tetragonolobus* contain a lectin that is specific for type *O* red cells. A number of other lectins have been found to be specific for types *A* and *O*. The search for an anti-*B* lectin took a long time, but recently Irwin J. Goldstein of the University of Michigan isolated a *B*-specific lectin from the seeds of *Bandeiraea simplicifolia*.

The specificity of some lectins is so sharply defined that they can distinguish among blood subgroups. The lectin of the legume *Dolichos biflorus,* for example, reacts more strongly with red cells of type A_1 than with those of type A_2. Lectins are also specific for particular types in another human blood group: they distinguish between the *M* and *N* types. Blood is routinely typed with the anti-*A* or anti-*B* antibodies that are present in blood serum, but lectins are also a useful tool for typing. One reason is that no natural anti-*O* antibody is available. Moreover, lectins are usually relied on for the diagnosis and typing of "secretors": people who secrete glycoproteins that have blood-group specificity into their saliva, urine and other body fluids.

The connection between blood-group specificity and sugars was established in 1953 by Watkins and Morgan. They showed that the agglutination of type *A* red cells by the lima bean lectin is best inhibited by the sugar *N*-acetylgalactosamine, and thus pinpointed that sugar as a determinant of type *A* specificity. The agglutination of type *O* cells by the type-*O*-specific lectin of *Lotus tetragonolobus* was found to be best inhibited by the sugar fucose, which was thus shown to be a determinant of type *O* specificity. Both conclusions have been substantiated by subsequent investigations. The early work of Watkins and Morgan was, incidentally, among the first pieces of evidence for the presence of sugars on cell surfaces.

The various biological activities of lectins I have described all stem from a single property: their ability to bind sugars. Each molecule of a lectin has two or more regions, perhaps clefts or grooves, each of which fits a complementary molecule of a sugar or several sugar units of an oligosaccharide. It is by means of these combining sites that the lectin attaches itself to the sugars on cell surfaces. With a battery of lectins that differ in their specificity (because they have combining sites with different shapes) it is therefore possible to learn a great deal about the composition of a cell's surface.

I have mentioned that the lima bean lectin is specific for *N*-acetylgalactosamine and the lectin of *Lotus tetragonolobus* for fucose. My colleague Halina Lis and I have found that soybean agglutinin is also specific for *N*-acetylgalactosamine but less restrictively so: soybean agglutinin binds to *N*-acetylgalactosamine equally well whether the sugar's molecules are linked in the alpha or the beta configuration, whereas the lima bean lectin binds only to *N*-acetylgalactosamine molecules that are alpha-linked. Both configurations may be encountered on cell surfaces, but the specificity determinant of blood type *A* is alpha-linked *N*-acetylgalactosamine. The lima bean lectin is therefore specific for blood type *A,* whereas soybean agglutinin is not blood-type specific.

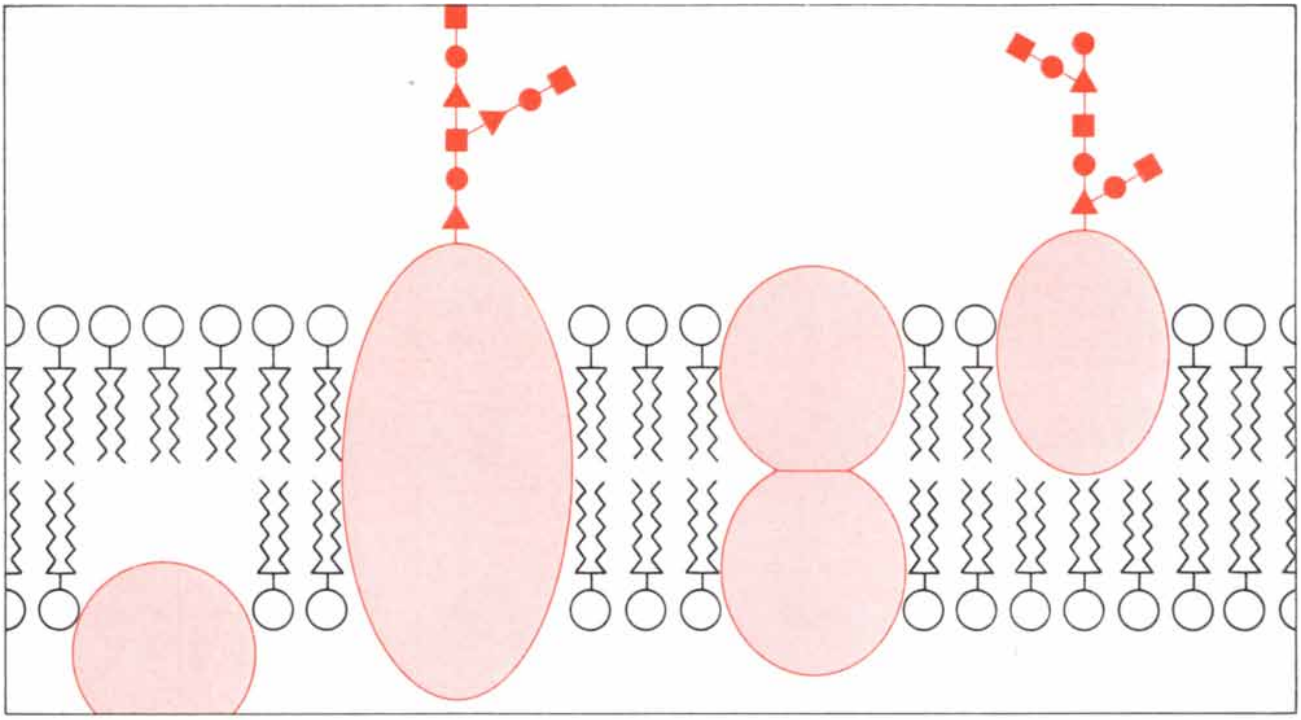
In addition to *N*-acetylgalactosamine, soybean agglutinin binds galactose and therefore precipitates from solution such glycoproteins as collagen, in which galactose occupies a terminal position. Wheat-germ agglutinin, in contrast, does not react with collagen; it is specific for oligosaccharides built up of *N*-acetylglucosamine and will therefore combine with chitin, a polymer of *N*-acetylglucosamine, or with ovomucoid, which is rich in that sugar. With the proper lectins one can separate polysaccharides and glycoproteins from one another or pluck glycoproteins out of mixtures with proteins and other compounds devoid of sugars.

The binding of lectins to sugar is quite weak. It does not result in the formation of covalent bonds but is reversible, like the reaction of an enzyme with a substrate or of an antibody with an antigen. Indeed, the precipitation reaction between a lectin and suitable polysaccharides or glycoproteins is analogous in almost every respect to an antibody-antigen system, in which the lectin plays the role of antibody and the polysaccharide or glycoprotein the role of antigen. In both systems, for example, the precipitate that is formed will usually dissolve when either one of the reactants is present in excess. The inhibition by specific sugars of the formation of a precipitate between a lectin and a polysaccharide (or glycoprotein) is analogous to the action of haptens, small molecules that combine with particular antibodies and thus inhibit the formation of a complex by an antibody and the corresponding antigen.

It has even been suggested that lectins are plant antibodies. There are, however, very striking differences between the two classes of proteins. The most important difference is that antibodies are products of the immune system of higher animals, in which they are manufactured in response to stimulation by a foreign substance that has entered the body; lectins, on the other hand, are present as constituent proteins of their organisms, and predominantly of organisms, such as plants, that are incapable of an immune response and of forming antibodies. Another difference is that the specificity range of antibodies is broad, encompassing not only sugars but also many other classes of compounds such as amino acids, proteins and nucleic acids (although each antibody is, of course, specific for the antigen that elicits its formation). No lectin has been found that is specific for compounds other than carbohydrates.

A third difference is in chemical structure. All antibodies are structurally similar to one another, whereas the lectins are structurally diverse; examination of the amino acid composition, molecular size and other molecular properties of many lectins shows that they have very little in common except that they are all proteins. For example, soybean agglutinin is a glycoprotein that has no sulfur-to-sulfur bonds in its molecule; its molecular weight is 120,000, it consists of four subunits and it has two binding sites. Wheat-germ agglutinin is not a glycoprotein and is rich in sulfur-to-sulfur bonds; its molecular weight is 36,000, it is made up of two identical subunits and it has four binding sites for sugars.

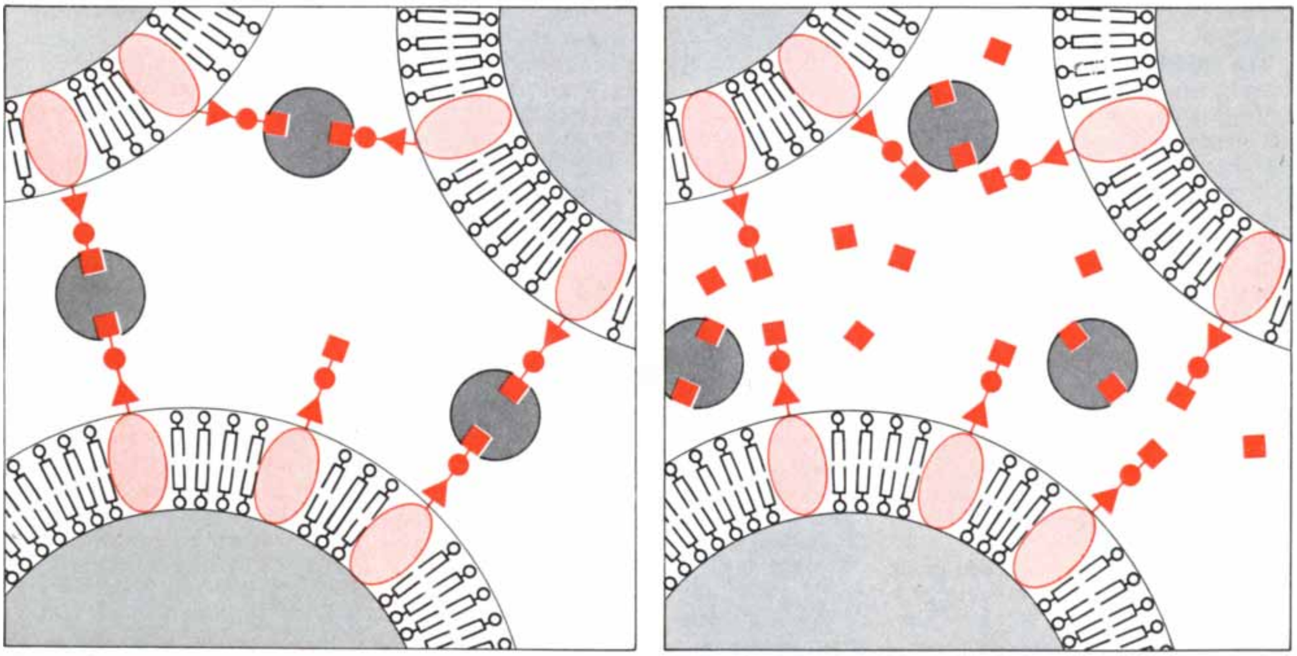
No other property of lectins has contributed to their importance in biological research as much as has their ability to preferentially agglutinate malignant cells. As often happens, this property was discovered by chance. The discovery was reported in 1963 by Joseph C. Aub at the Massachusetts General Hospital in Boston, on the basis of research conducted after he had retired from the Harvard Medical School. Aub was one of the very few investigators who at that



CELL MEMBRANE is an assembly of lipids and proteins. A bilayer of lipid molecules, each with a water-soluble head and a water-repellent double tail, forms the structural framework. Protein molecules (*color*) lie on the surfaces of the bilayer or are embedded in it. Some of the proteins are glycoproteins, with branching chains of sugar units (*dark color*) to which particular lectins can bind. Usually some of the membrane lipids are glycolipids (not shown here), in which case their protruding sugar chains also take part in the binding of the lectins.

time believed the difference between cancer cells and normal cells lay in their surface: that alterations in cell-surface properties enabled cancer cells to continue to multiply when normal cells do not and to detach from their original site, spread through the body, lodge in a new environment and set up new colonies there.

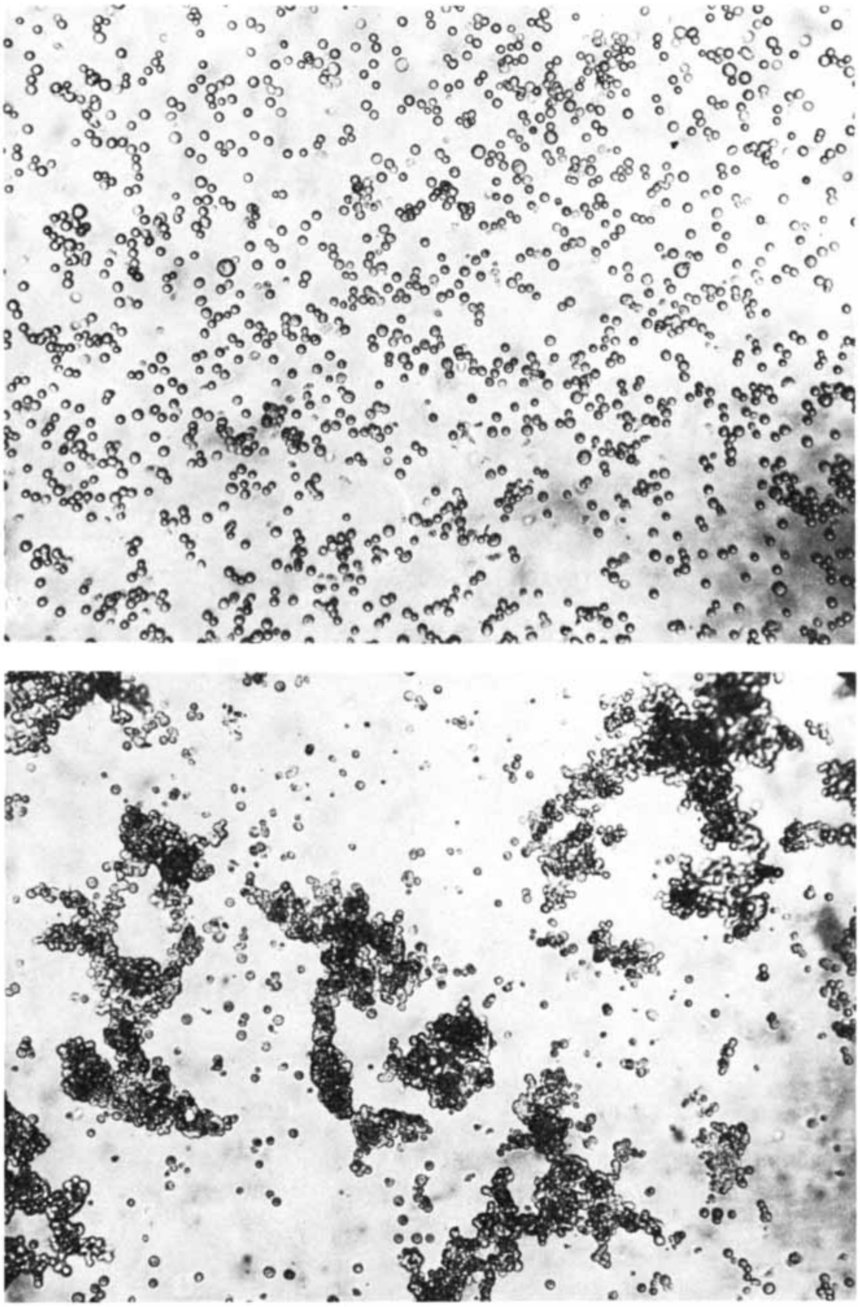
Such ideas seemed quite strange at the time; most investigators considered them completely unfounded, something bordering on lunacy. To find out whether the surface of malignant cells is different from that of normal cells, Aub examined their response to incubation with several enzymes. Only in the case of one of the enzymes, a lipase from wheat germ, did he observe a difference: normal cells did not seem to be affected by the enzyme, but malignant cells



AGGLUTINATION is the result of cross-linking of cells by lectins (*dark gray*) that bind to specific receptors: sugar units of oligosaccharide chains protruding from the cell surface (*left*). Agglutination is inhibited or prevented if the monosaccharide that is responsible for the binding is added to the cell suspension, because the monosaccharide occupies and preempts combining sites on the lectins (*right*).

were agglutinated. When he replaced the wheat-germ lipase with a pancreatic lipase, however, no agglutination was observed with either cell type. Further examination of the wheat-germ lipase showed that the enzymatic activity of the preparation could be abolished by heating, whereas the agglutinating effect was not abolished. Aub and his colleagues then found that the wheat-germ lipase preparation contained as a contaminant a small protein that was responsible for the agglutinating activity. This protein is now known as wheat-germ agglutinin.

Aub's discovery began a new era in lectin research. It was immediately followed by the purification of wheat-germ agglutinin by Max M. Burger of Princeton University, who conducted with it extensive studies of the surface changes that attend the malignant transformation of cells. Wheat-germ agglutinin was not available commercially, however, and it was not easy at the time to prepare it in purified form. It was only after Leo Sachs and Michael Inbar of the Weizmann Institute found that concanavalin *A* also agglutinates malignant cells that lectins became commonplace in many biological laboratories, because concanavalin *A* is available commercially and is relatively inexpensive. Sachs, Ben-Ami Sela, Halina Lis and I found that soybean agglutinin will also distinguish between normal and malignant cells, and other lectins have since been shown to possess the same property. As a rule malignant cells are agglutinated by very low concentrations of such lectins (10 to 15 micrograms per milliliter), whereas normal cells are not agglutinated unless the concentration of the lectin is at least 10 to 20 times higher. (There are a few exceptions: some tumor cells are not agglutinated by low concentrations of a particular lectin and some types of normal cells are agglutinated even by low concentrations of a lectin.)

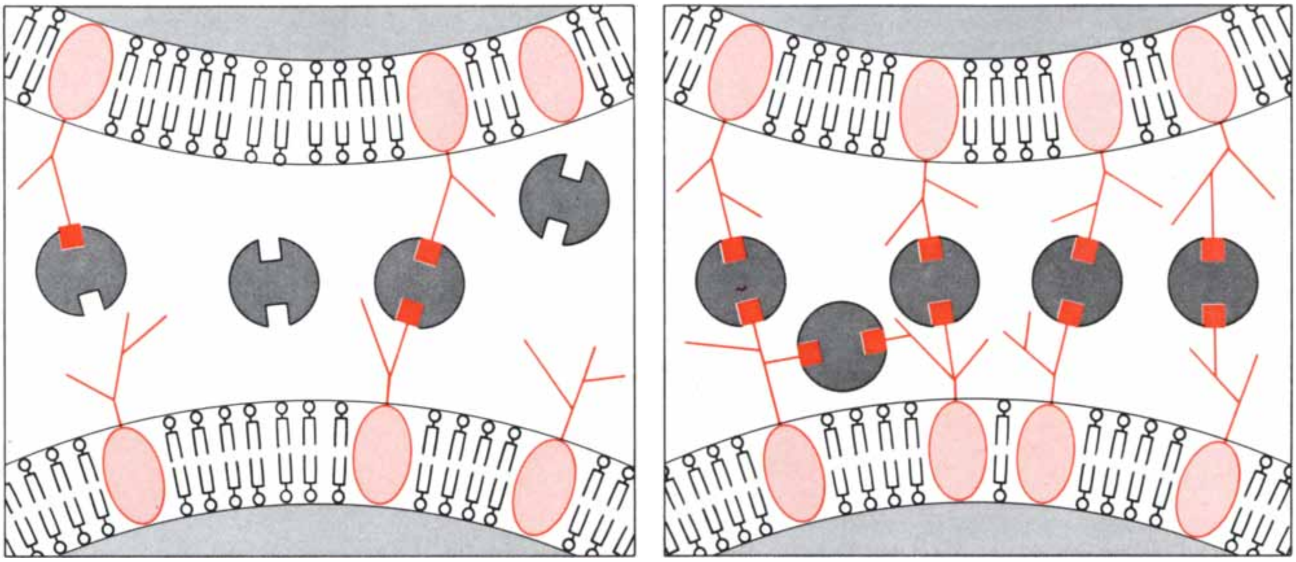


PREFERENTIAL AGGLUTINATION of malignantly transformed cells is demonstrated in a photomicrograph made in the author's laboratory. Normal rat cells (*top*) and rat cells transformed by polyoma-virus infection (*bottom*) were incubated for 30 minutes with a lectin, soybean agglutinin. There was massive agglutination of transformed cells but not of normal ones.

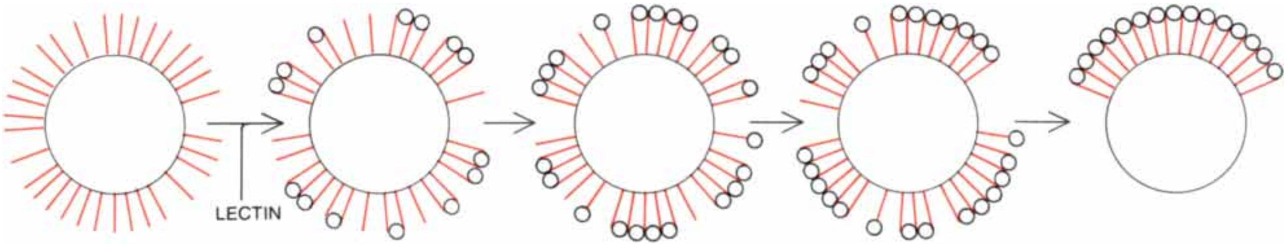
Burger made the interesting observation that even among normal cells that are in general not agglutinated by a lectin there is always a small proportion that are. He identified the agglutinated cells as being in the process of mitosis, and so he concluded that during mitosis the surface of normal cells is to some extent similar to that of transformed cells. This suggested to him the existence in the cell cycle of a critical switching point. According to Burger, malignant transformation may operate like the throwing of a switch that sidetracks the cell from its normal cycle, in which there is a slowdown or an almost complete halt after mitosis, and heads it toward continued, nonstop division. Although we still do not understand how this "switch" operates, it may be helpful for future research to keep in mind the possibility that there is a critical point in the cell cycle when any normal cell can either be steered toward quiescence or be transformed and thus shunted toward malignant growth.

We are still far from understanding exactly how the surface of the cell changes in the course of malignant transformation. The studies with lectin have convinced many workers that the cell membrane plays a central role in modulating the control of growth, but it is not known how the control is effected. Much more research is also needed before it is clear whether the cell-surface alterations detected with lectins are merely correlated with transformation or have a causal role in the malignant process.

In addition to detecting the cell-surface changes during malignant transformation, lectins are providing evidence that the cell surface is altered in the course of embryonic cell differentiation. In 1971 Aaron A. Moscona of the University of Chicago first demonstrated that the effect of concanavalin *A* on nerve cells in the retina of the chick embryo depended very much on their embryonic age. Dispersed cells from young (eight-to-nine-day) embryos were agglutinated rapidly and massively by conca-



PREFERENTIAL AGGLUTINABILITY of the transformed cells is apparently due to the higher local density of lectins on the surface of such cells. The number of bound lectins is about the same on normal cells (*left*) as it is on transformed cells (*right*). On the transformed cells, however, the lectin receptors are closer together, so that more cross bridges can be formed in a given area. Evidence for such redistribution of bound lectins comes largely from micrographs of labeled lectin molecules, such as those at top of the opposite page.



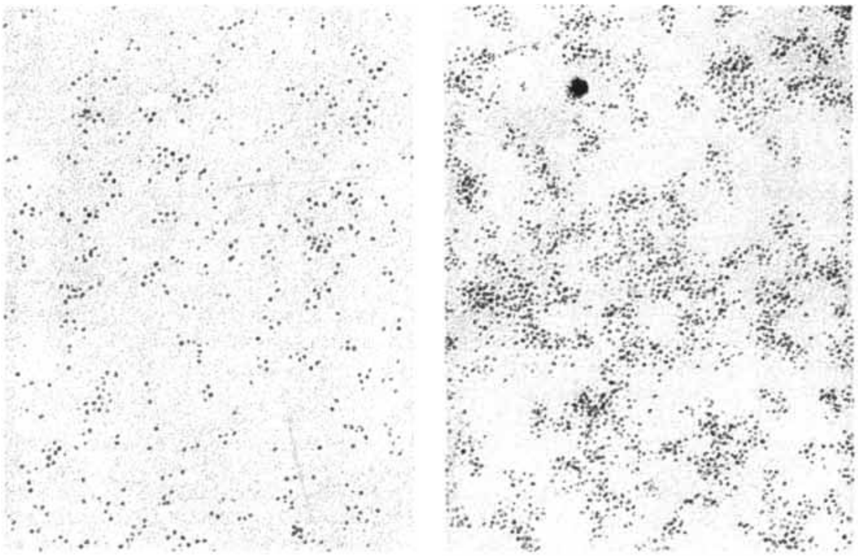
LECTIN RECEPTORS (*colored lines*) are apparently randomly distributed over the surface of a normal or a malignantly transformed cell in the absence of a lectin (*left*). Addition of a lectin (*small circles*) having several combining sites interconnects receptors, aggregating them first into clusters and then into larger patches, and finally assembling them into a single "cap" at one site on the surface of cell.

navalin *A*. The effect changed as the retinal cells differentiated and matured, so that 20-day cells agglutinated only very poorly, if at all, even with large doses of concanavalin *A*. Changes in the agglutination pattern of cells in the course of differentiation were also detected with other lectins. These results clearly show that with differentiation the carbohydrate-containing molecules on the retinal-cell surface undergo striking alterations, which Moscona thinks must be an integral aspect of the overall differentiation program of the cells.

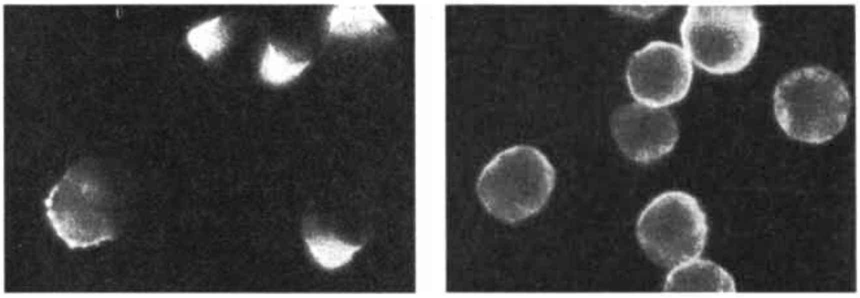
I pointed out above that the nature of the cell-surface changes monitored by lectins is far from being understood. How can this be so when the changes are detected by a test as simple as cell agglutination? The fact is that in spite of its seeming simplicity, cell agglutination has proved to be a highly complex phenomenon in which many factors operate. There is no doubt that for cells to agglutinate, the lectin molecules that attach to sugar molecules on the cell surface must form bridges between the cells. As a simple corollary it was first assumed that when cells did not agglutinate, it was because either the cells were not binding lectin molecules to their surface at all or the amount being bound was very small.

Quite surprisingly this did not prove to be the case. Measurement of binding sites with radioactively labeled lectins showed that whether cells were agglutinated by the lectin or not, the total number of lectin molecules bound to their surface was usually the same. For example, virally transformed cells that were agglutinated by 10 to 20 micrograms per milliliter of soybean agglutinin could each bind nearly 10 million molecules of the lectin; the same number of lectin molecules were bound by the normal cells from which the malignant cells were derived, in spite of the fact that the normal cells were not agglutinated even when they were incubated with 500 micrograms of soybean agglutinin per milliliter. Moreover, when normal cells are treated with proteolytic enzymes to remove their surface proteins and glycoproteins, they become as sensitive as transformed cells to agglutination by lectins, although the proteolytic treatment does not change the number of lectin molecules on the cell surface.

Many attempts have been made to explain these puzzling observations. One of the popular explanations is based on experiments with lectin molecules labeled by fluorescent dyes, so that their location on the cell can be determined with the light microscope, or by ferritin, which reveals their location on the surface in an electron micrograph. Such experiments show a difference in the surface distribution of lectins bound to normal cells and that of lectins bound to tumor cells. On normal cells the lectin molecules are distributed randomly, whereas on the surface of tumor cells



SURFACES of a normal mouse cell (*left*) and of a cell transformed by SV40 (*right*) are enlarged 100,000 diameters in electron micrographs made by Garth L. Nicolson of the Salk Institute. Both cells were incubated with concanavalin *A* labeled with electron-dense ferritin. The lectin is evenly dispersed on the normal cell, aggregated into clusters on the transformed cell.



CAPS FORM ON SURFACE of mouse leukemic cells incubated with concanavalin *A* labeled with fluorescent dye (*left*), but not if cells are fixed with glutaraldehyde to immobilize receptors before lectin treatment (*right*). Experiment indicates that lectins pull receptors together.

they appear to be aggregated into clusters. As a result they can form multiple cross bridges between cancer cells, and this cooperative formation of bridges accounts for the greatly increased agglutinability of malignant cells compared with that of normal cells.

If the lectin molecules are clustered, it must be because their saccharide receptors have been clustered. What moves the receptors: the process of malignant transformation or the application of a lectin? Investigation suggests that the clustering is induced by the lectin molecules but is made possible by transformation. If one limits the mobility of the membrane components of tumor cells (by cooling the cells or fixing the membrane with glutaraldehyde) before lectin treatment, those tumor cells show the same random distribution of bound lectin molecules that normal cells do. If the lectin is applied to cells at 37 degrees Celsius, however, or before glutaraldehyde treatment, the clustered distribution is attained within minutes. The clustering is thought to be a passive process, in which the lectin molecules somehow pull the receptors together, the receptors diffusing through the lipid bilayer of the membrane. It appears, in other words, that the membrane of a malignant cell is more fluid (less viscous) than that of a normal cell.

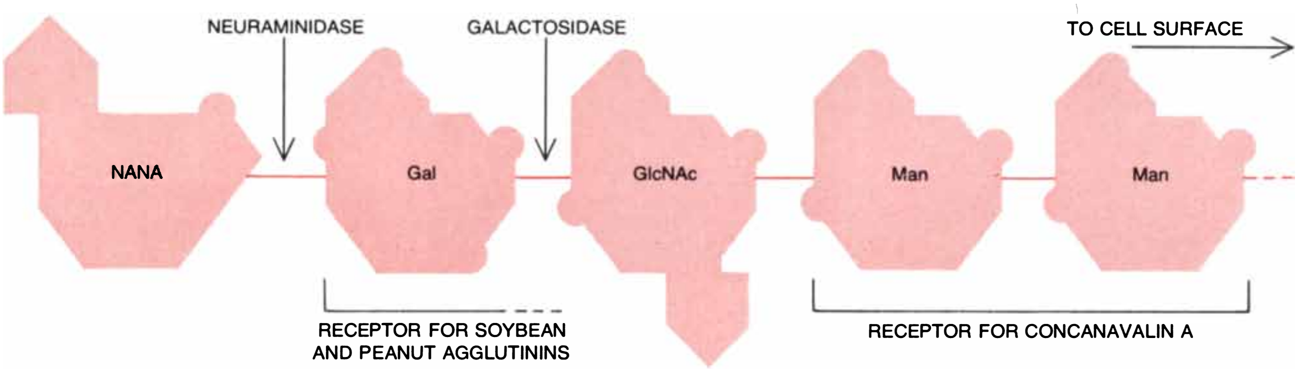
It has been postulated that increased fluidity of malignant-cell membranes could account, at least in part, for some other characteristics of these cells, such as their decreased "stickiness," their ability to migrate through the body from their tissue of origin and probably their loss of "contact inhibition" of growth. (Normal cells grown in culture stop dividing when they touch one another, whereas malignant cells continue to grow and pile up.) Surface alterations, then, may largely explain the tendency of cancer cells to grow without regard to their neighbors.

Lectins are playing an increasing role

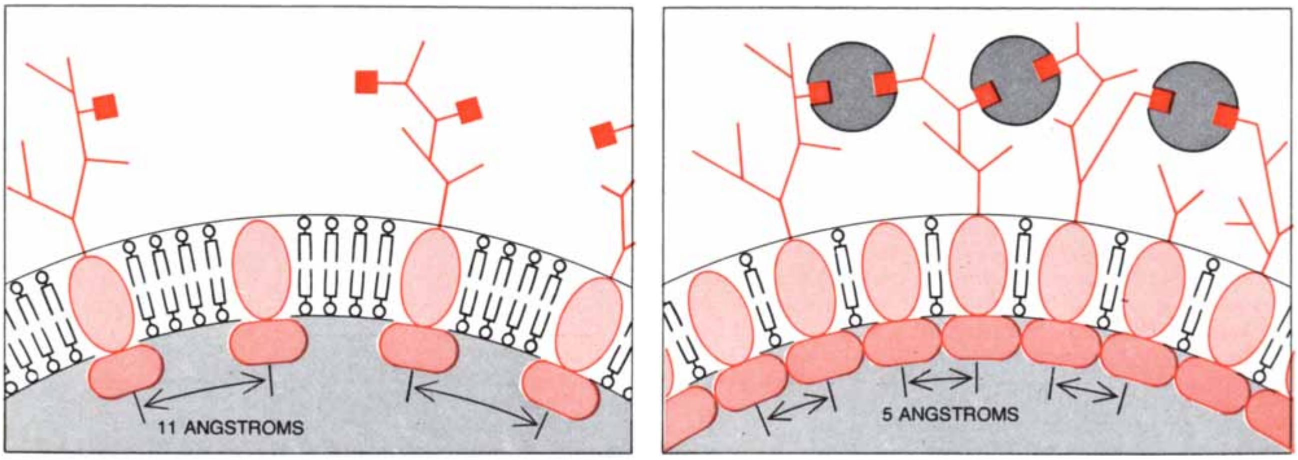
in immunology, helping to provide an answer to one of the fundamental problems: What is the mechanism by which an antigen, acting at the cell surface, specifically triggers lymphocytes to grow, mature and proliferate, and in some cases to synthesize antibodies? A major difficulty in investigating this problem had been that only a few (usually less than one in 1,000) of the *T* lymphocytes (derived from the thymus) or the *B* lymphocytes (derived from the bone marrow) bind any particular antigen and are stimulated by it. The discovery in 1960 by Peter C. Nowell of the University of Pennsylvania School of Medicine that phytohemagglutinin, the lectin of the red kidney bean, can stimulate lymphocytes not only was of major importance for chromosomal analysis (and for the study of lectins themselves) but also was crucial in shaping our ideas on the functions of lymphocytes. PHA and the other lectins that are now known to be mitogenic are important because they stimulate lymphocytes to grow and divide regardless of the antigenic specificity of the lymphocyte receptors, so that a large proportion of the lymphocytes in a preparation can be stimulated and analyzed.

The gross changes in size and shape and biochemical events observed in lectin-stimulated lymphocytes in the laboratory appear to resemble many of the antigen-induced immune reactions in the living animal. *B* lymphocytes stimulated by lectins are capable of synthesizing immunoglobulins much as cells do when stimulated by antigens in laboratory glassware; *T* lymphocytes may be turned into "killer cells" that destroy any foreign cells they encounter just as they do when they reject grafted tissue. In addition to their function in fundamental studies on the mechanism of the immune response and as a diagnostic tool for detecting hereditary and acquired immunological deficiencies, mitogenic lectins are effective for detecting sensitization caused by infectious agents or in some autoimmune diseases and for monitoring the effects of various forms of immunotherapy.

Studies of mitogenic stimulation by lectins have provided important information on the structure and organization of saccharides on the cell surface. Like agglutination, mitogenic stimulation is a result of the binding of a lectin to the saccharide units of glycoproteins or glycolipids on the cell surface; the first proof of this came when it was found that the mitogenic activity of concanavalin *A* could be abolished by adding a solution of mannose or glucose to lymphocytes incubated with the lectin. Similar experiments reveal the composition of receptors in detail. Studies carried out in our department, mainly by Abraham Novogrodsky, showed, for example, that the two galactose-specific lectins, soybean agglutinin and peanut agglutinin, would not stimulate rat lymphocytes unless the sugar called sialic (or neuraminic) acid was removed from the surface of the cells. If galactose was subsequently removed, the cells were no longer stimulated by soybean or peanut lectins, but they remained responsive to concanavalin *A*. These results can be explained by assuming that on the lymphocyte surface the sugars are arranged



STRUCTURE of the polysaccharide that serves as a lectin receptor on the surface of lymphocytes is established by successively removing specific sugar units with specific enzymes. Removal of neuraminic acid makes possible the binding of galactose-specific lectins; removal of galactose prevents the binding of those lectins but leaves the cell still sensitive to concanavalin *A*, which binds mannose units.



TRANSMEMBRANE EFFECT was demonstrated by Nicolson and Tae H. Ji of the University of Wyoming with red-blood-cell membranes, one of whose proteins, spectrin (*medium color*), is on the inner face. The spectrin molecules could be cross-linked by a reagent about 11 angstroms long (*left*). The addition of a lectin apparently aggregated glycoproteins spanning the membrane, which in turn moved the spectrin molecules on the inner face of the membrane, so that they could be cross-linked by a reagent only five angstroms long (*right*).

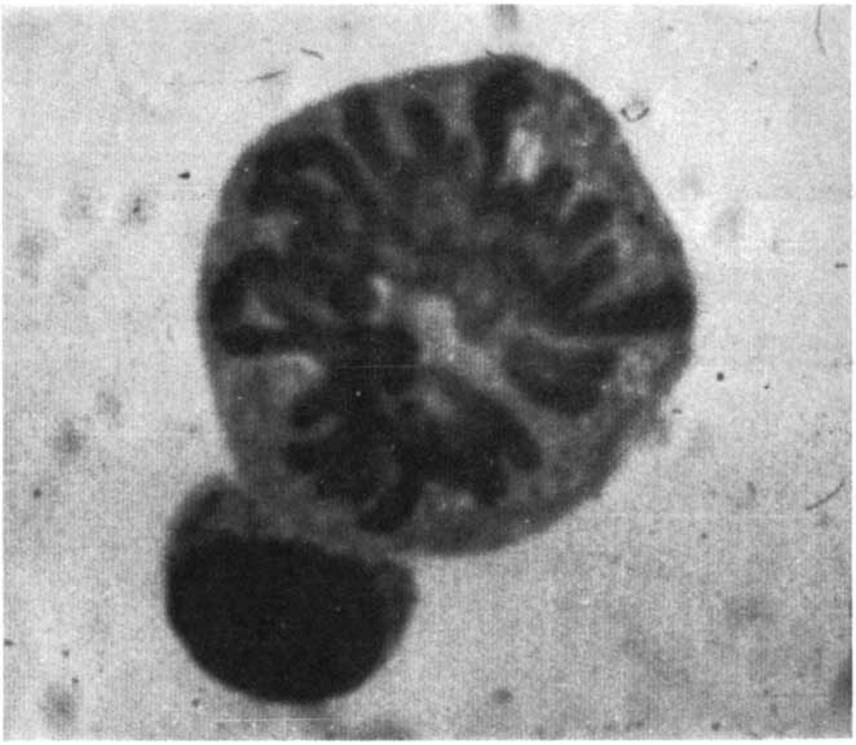

GETTING PEOPLE TOGETHER.

in a sequence that is found in many glycoproteins, with neuraminic acid at the outer end of the chain followed by galactose and mannose [*see upper illustration on page 116*], and that the sequence is part of the cell-membrane receptor sites for soybean and peanut agglutinin and concanavalin *A*, binding to which results in mitogenic stimulation.

The experiments on the triggering of lymphocytes by lectins demonstrate that it is initiated by events on the membrane, but by what molecular mechanism is the signal carried across the membrane? One suggestion is that the signal is mediated by the clustering of the receptors in the fluid membrane. An indication for the existence of such transmembrane effects has been obtained by Garth L. Nicolson of the Salk Institute and Tae H. Ji of the University of Wyoming. They worked with red-cell membranes, which are easier to prepare than lymphocyte membranes and concerning which more is known. The red-cell membrane contains glycoproteins that appear to span its lipid bilayer and other proteins, notably one known as spectrin, that are on its inner (cytoplasmic) face. Nicolson and Ji "measured" the distance between neighboring spectrin molecules in the isolated membrane by attempting to cross-link them with a chemical agent whose length can be varied. In the isolated membrane cross-linking could not be effected unless the linking reagents were about 11 angstroms long. After lectins such as concanavalin *A* or castor-bean agglutinin were bound to the outer surface of the membrane, on the other hand, cross-linking of the spectrin on the inner face could be achieved even with a reagent that was five angstroms long.

It remains to be seen how general such transmembrane effects are. If the effect of the aggregation of lectin receptors on the surface of lymphocytes is transmitted to the cell interior by lymphocyte-membrane glycoproteins, other proteins could be redistributed that are on the inner surface of the membrane. Being in direct contact with the cytoplasm and through it with the nucleus, those inner proteins could somehow set the cell machinery going.

When one studies mitogenic stimulation or any other properties of lymphocytes, the task is complicated by the great heterogeneity of these cells: even lymphocytes taken from a single organ—say the thymus—consist of several subpopulations, which differ in their properties and biological functions. It is therefore essential to separate lymphocytes into homogeneous subpopulations if one is to correlate their properties with their biological role and understand the mechanisms of their response



MITOGENIC EFFECT of a lectin is demonstrated in a photomicrograph made by Abraham Novogrodsky. A stained mouse-spleen lymphocyte has entered the metaphase stage of mitosis, in which it is enlarged and its chromosomes are discrete structures, after incubation for three days with concanavalin *A*. An unstimulated lymphocyte is seen next to the stimulated cell.

to various stimuli, but no efficient methods are yet available for separating lymphocytes according to their biological functions.

Yair Reisner and Mariana Linker-Israeli of the Weizmann Institute have recently demonstrated that lectins may provide an answer to this problem. They separated mouse thymus cells into two subpopulations: one that is agglutinated by peanut lectin and one that is not. The two subpopulations were found to differ in their surface antigens and in their response to the mitogenic activity of PHA. The thymocyte subpopulation that was not agglutinated by peanut agglutinin is similar in its properties to the circulating *T* lymphocytes; in particular it is active in tests for graft rejection. Only this subpopulation, which is thought to be maturer than the majority of the thymus lymphocytes, has a high content of sialic acid on its surface. It is possible that the attachment of sialic acid to the cell surface of lymphocytes is an important step in the maturation of these cells in the thymus.

Much progress has been made in the study of lectins, but many questions about their properties and functions remain unanswered. One intriguing question is: What value can lectins possibly have for the organisms that produce them? Why should a lima bean or a snail possess a protein that can distinguish between different human blood types, identify malignant mammalian cells and stimulate lymphocytes? So far there is no convincing answer to the question, but a possible answer has recently emerged from studies in our laboratory. Reuben Lotan, David Mirelman and I, in collaboration with Esra Galun of the Weizmann Institute's department of plant genetics, have found that wheat-germ agglutinin inhibits the growth of certain fungi that contain in their cell walls chitin, which is a polymer of *N*-acetylglucosamine. On the basis of this finding we have proposed that wheat-germ agglutinin protects wheat against fungi and other chitin-containing plant pathogens during the early swelling of the seed, germination and early seedling growth. Perhaps lectins with a sugar specificity differing from that of wheat-germ agglutinin inhibit the growth of other plant-pathogenic microorganisms whose surface is covered with polysaccharides made up of other sugars. Whatever the role of lectins in nature is, there is no doubt that they will continue to serve as an important aid in the process of charting the complex landscape of cell surfaces, in clarifying the role of surface sugars in cellular behavior and growth and thus in deepening our understanding of the biology of cells, normal and malignant alike.

Medina inven.

Burg. sculp.

Poetic Responses to the Copernican Revolution

English poetry of the 17th century imaginatively reflected man's new awareness of a vaster universe. Yet the poetic imagination was rooted in the past and in the end lost its place as a bridge to new knowledge

by Margaret M. Byard

And new Philosophy cals all in
doubt,
The Element of fire is quite put
out;
The Sun is lost, and th'earth, and no
mans wit
Can well direct him, where to looke
for it.

John Donne wrote those lines shortly after Galileo had trained his three-power telescope on Jupiter and found four bright moons circling the planet in a miniature model of the solar system, a discovery that lent credence to the Copernican hypothesis that the earth circled the sun and was therefore not the center of the universe. In 17th-century England, where men of rich imagination and language were equal to the occasion, the revolution begun by Copernicus and accelerated by Galileo inspired poetry in which the dismay expressed by Donne gradually gave way to exultation in the new universe of infinite space. The poets were not always precise about how the cosmos had been rearranged; they often invoked the old earth-centered Ptolemaic plan. Blended with such errors, however, was a new awareness of spaciousness, expressed in imagery that ranged across the cosmos, soaring into realms far beyond the celestial spheres in which the planets and the stars had hitherto been confined. The combination of the old and the new yielded poetry of a unique beauty pervaded by a sense of wonder and a singular freshness of vision. Intensely religious as they were, these poets found that the new concepts of the universe fulfilled their ideas of a deity of infinite power and creativity.

To put oneself in the poet's place and to respond to his metaphors one must recall first the model of the universe he had inherited from the past and then the discoveries that burst open its boundaries and freed the tiny "punctual spot of earth" into a sea of stars. Until late in the 16th century the poet, like any other literate citizen, could think of himself as being the focus of a visible cosmos. Looking up at the heavens, he could see the moon circling the earth to illuminate it by night and the sun, that "busy old fool," rising and setting to illuminate it by day. The planets, set like jewels in their celestial spheres, also obediently circled the earth, and beyond them, set in their own sphere, revolved the "fixed" stars visible to the unaided eye, stars that were perfect, unchanging, divinely numbered, placed there by God. Each planet and star had a role in man's life and watched over his terrestrial affairs. Visible in the heavens but not included in the model was the Milky Way, explained by ancient myth as the copious output of Venus' breasts.

The regions below the moon were imperfect and subject to decay. Immediately below the moon was the region of fire, constantly aflame yet transparent. Below the region of fire were the regions of air, water and the solid earth.

BATTLE IN HEAVEN in Milton's *Paradise Lost* is conducted on several planes. Here the battle between Satan and God, as reenacted before Adam and Eve in Book VI, is portrayed in the first illustrated edition of the work published in 1688. According to the argument at the beginning of Book VI, "God on the third day sends *Messiah* his Son, for whom he had reserv'd the glory of ... Victory: He in the Power of his Father coming to the place [of battle], and causing all his Legions to stand still on either side, with his Chariot and Thunder driving into the midst of his Enemies, pursues them unable to resist towards the wall of Heaven; which opening, they leap down with horrour and confusion into the place of punishment prepar'd for them in the Deep." Although Milton's message in *Paradise Lost* was theological and political, the awareness of space that was brought about by the revolutionary cosmology of Copernicus, Kepler and Galileo gave him a vast arena for his account of struggle between good and evil.

Of primary importance was the interconnectedness of the plan. Man's body was made up of the four elements fire, air, water and earth and was regulated by the fixed stars. Since before the time of Plato it had been believed the world had a soul like man's own. Man's form and proportions were a pattern for all structure, including the structure of the universe.

Into this compact ancient model broke a brilliant new star in 1572 (Tycho's nova), a great comet in 1577 and another brilliant new star in 1604 (Kepler's nova). These events were a disaster to literal believers in the ancient cosmology but a liberation for those mathematician-astronomers who for centuries had been struggling to reconcile fantasy and observation. The evidence accumulated. Copernicus had published his finding of the sun's centrality in 1543, but there was no telescope to help prove his assertion. Working with ambitious but inadequate medieval instruments, Tycho Brahe calculated that the visible planets revolved around the sun. By determined ingenuity, however, he demonstrated that the sun, along with the planets, circled the earth. Johannes Kepler further ruined the comfortable old pattern of perfection by showing that the planets traveled around the sun in elliptical paths. He retained the ancient notion of the music of the spheres, but the complicated orbits meant that each planet contributed a full melody to the heavenly sound rather than a single tone. Galileo and his irrefutable observations doomed the old earth-centered cosmology. He announced that the sun is indeed central and the earth is its satellite, and not even the principal one. Moreover, through his "optic glass" the mysterious milk of Venus was seen to consist of faint stars in uncountable millions.

Gradually the new ideas diffused throughout Europe. They arrived in England at a time—the time of Shakespeare—when poetic expression in the English language was at a peak never attained before or since. The poetic tradition was also strong: as one of a long line descended from David and Orpheus the poet could still write as an interpreter of the truths of nature. The *Poly-Olbion* (1612) of Michael Drayton is a gazetteer of England in verse form; *The Purple Island* (1633) of Phineas Fletcher is an anatomy of the body in archaic terms; *Democritus Platonissans* (1646) of Henry More is a faithful description of the Copernican solar system embedded in a "Platonic" poem. It was almost as if the writers had to veil their knowledge in a cloud of poetry.

Where the Latin letters and treatises of Kepler, Galileo and their successors were addressed to astronomers and mathematicians, the poets spoke in common English to the wider circle of the literate. One can see in their work a growing awareness of a larger universe, of space and of infinity. Yet at the same time they retained the outlook of the old cosmology: man was still the center of things bound in a close relation with the planets and the stars.

The canon of space poetry, defined 40 years ago by the literary historian Marjorie Hope Nicolson, begins with Donne. In his "worst voluptuousness, an hydroptic, immoderate desire of human learning and languages," he was associated with the learned university men of his day. Thomas Hariot, the English astronomer who was one of the first to use the telescope, can be connected with Donne through mutual friends and associates. Evidence of Donne's scientific sophistication comes from *Ignatius his Conclave,* a satire that describes an imaginary descent to hell, where "innovators" such as Galileo and Kepler are disposed of. Galileo, Donne says, "of late hath summoned the other worlds, the Stars, to come neerer to him, and give him an account of themselves.... Kepler...ever since Tycho Braches death hath received it into his care, that no new thing should be done in heaven without his knowledge."

Even Donne's love poems are alive with imagery of suns, moons and stars. It cannot be said of these poems that Donne was entering the mysteries of a newly discovered cosmos; his imagery is almost always Ptolemaic. He is unique, however, in complimenting the women he celebrates with cosmic references. They must have been puzzled ("perplexed," said Dryden) by some of his mind-stretching comparisons. In "Elegie: Going to Bed" the lady's belt, as he removes it in exploring "my America! my new-found-land," is the zone of Orion. In "A Valediction of Weeping" each

"THE ORIGIN OF THE MILKY WAY," painted in the 16th century by Tintoretto (1518–94), portrays a pre-Galilean "common sense" explanation of the nature of the Milky Way based on ancient Greek myth: the luminous track seen across the sky was Venus' milk.

of his lover's tears as she weeps at their parting is like a globe or a new world. "O more then Moone," he calls her in the next stanza; the moon can only influence the tides but she creates tides in which he drowns.

In the poems Donne wrote for the great ladies who were his patronesses there is no mistaking cosmic hyperbole. The Countess of Bedford changes the entire celestial order; her brightness is such that she creates a new day, a new night, a new cosmos:

Out from your chariot, morning breaks
at night,
And falsifies both computations so;
Since a new world doth rise here from
your light,
We your new creatures, by new
recknings goe.

The Countess of Huntingdon, who shuns great titles, has been taught modesty by the constellations themselves, the greatest of which have taken modest names such as the Crab (Cancer) or the Bull (Taurus). How very different it is from the conventional compliments to which the dedicatees were accustomed: the beamy eyes, the sweet, swelling, sugared lips, the brows like Cupid's bows that Philip Sidney gave his Stella.

Later Donne's attitudes were to shift away from the easy commandeering of stars and moons as ornaments for his mistresses and patronesses. In his religious poetry, written as he was on his way to another life as the greatest preacher of his age, he spans aeons and immeasurable distances. In the most familiar of his *Holy Sonnets* Donne equates himself and the world: "I am a little world made cunningly / of Elements, and an Angelike spright." Less noticed are the next lines, in which he says that Christ is a discoverer who "beyond that heaven which was most high" has "found new spheares, and of new lands can write." Those are remarkable lines. In them Donne was admitting that heaven was most high and yet that there might be new spheres beyond the closed traditional world. Could he have been thinking of the infinity of worlds that had become a stronger possibility because of Galileo?

Donne's "The First Anniversarie" (1611) and "Of the Progres of the Soule" (1612) are laments for a dying world and a dying cosmology. In them one finds the dismay that was generally being experienced over what Nicolson called "the breaking of the circle," the demise of the Ptolemaic system.

And freely men confesse, that this
world's spent,
When in the Planets, and the
Firmament
They seeke so many new; they see that
this
Is crumbled out againe to'his Atomis.
'Tis all in pieces, all cohaerence gone....

Donne felt that the new science tears

The Firmament in eight and fortie
sheeres,
And in those constellations there arise
New starres, and old do vanish from
our eyes:
As though heav'n suffred earth-quakes,
peace or war,
When new Townes rise, and olde
demolish'd are.

Astronomers have "empayld within a Zodiake / The free-borne Sunne." Everything in the arrangement of the heavens is uncertain. No longer can one know when sun or stars will rise,

...nor can the Sunne
Perfit a Circle, or maintaine his way
One inche direct; but where he rose to
day
He comes no more, but with a cousening
line,
Steales by that point, and so is
Serpentine:
And seeming weary with his reeling
thus,
He meanes to sleepe, being now falne
nearer us.
So, of the Starres which boast that they
do runne
In Circle still, none ends where he
begunne.
All their proportion's lame, it sinks, it
swels.

The two poems are an interweaving of the old and the new. At the same time that they lament the old model of the universe, they carry the reader out toward the uncertain boundaries of space. However regretful Donne may be, his imagination has been loosed from the "little world." Yet he strongly retains the old close relation of man with the sun and the stars, writing of the celestial bodies as fellow sufferers in disintegration. Anthropomorphism, animism and the pathetic fallacy have here their most convincing and most moving expression:

For of Meridians, and Parallels,
Man hath weav'd out a net, and this net
throwne
Upon the Heavens, and now they are
his owne.

George Herbert, a younger contemporary of Donne and perhaps the greatest of English religious poets, also laments and dreads the vast universe. In the few short lines of "The Temper" (1633) he soars from the greatest heights above the earth to the limitless depths below, down into the unknown region of hell. It is notable that in the following lines heaven is not only receding but also multiplied, a change in conception that might not have occurred without new views of the structure of the universe:

Although there were some fourtie
heav'ns, or more,
Sometimes I peere above them all;
Sometimes I hardly reach a score,
Sometimes to hell I fall.

O rack me not to such a vast extent;
Those distances belong to thee:
The world's too little for thy tent,
A grave too big for me.

Yet unlike Donne, Herbert exults in the spacious universe he portrays, even as he retains the old sense of man's role in it and kinship with it. In his poem "Man" he writes: "The starres have us to bed; / Night draws the curtain, which the sunne withdraws." There are cupboards and cabinets in his outer space as there are in the library or study where the 17th-century collector kept his treasures:

Nothing hath got so farre,
But Man hath caught and kept it, as his
prey.
His eyes dismount the highest starre:
He is in little all the sphere.
Herbs gladly cure our flesh; because
that they
Finde their acquaintance there.

For us the windes do blow,

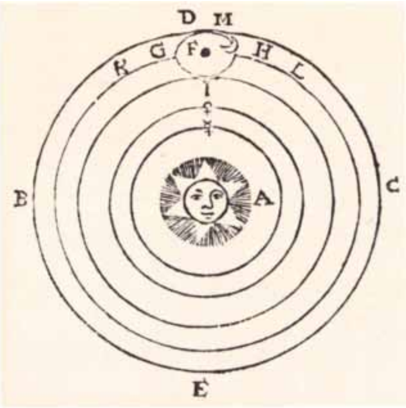
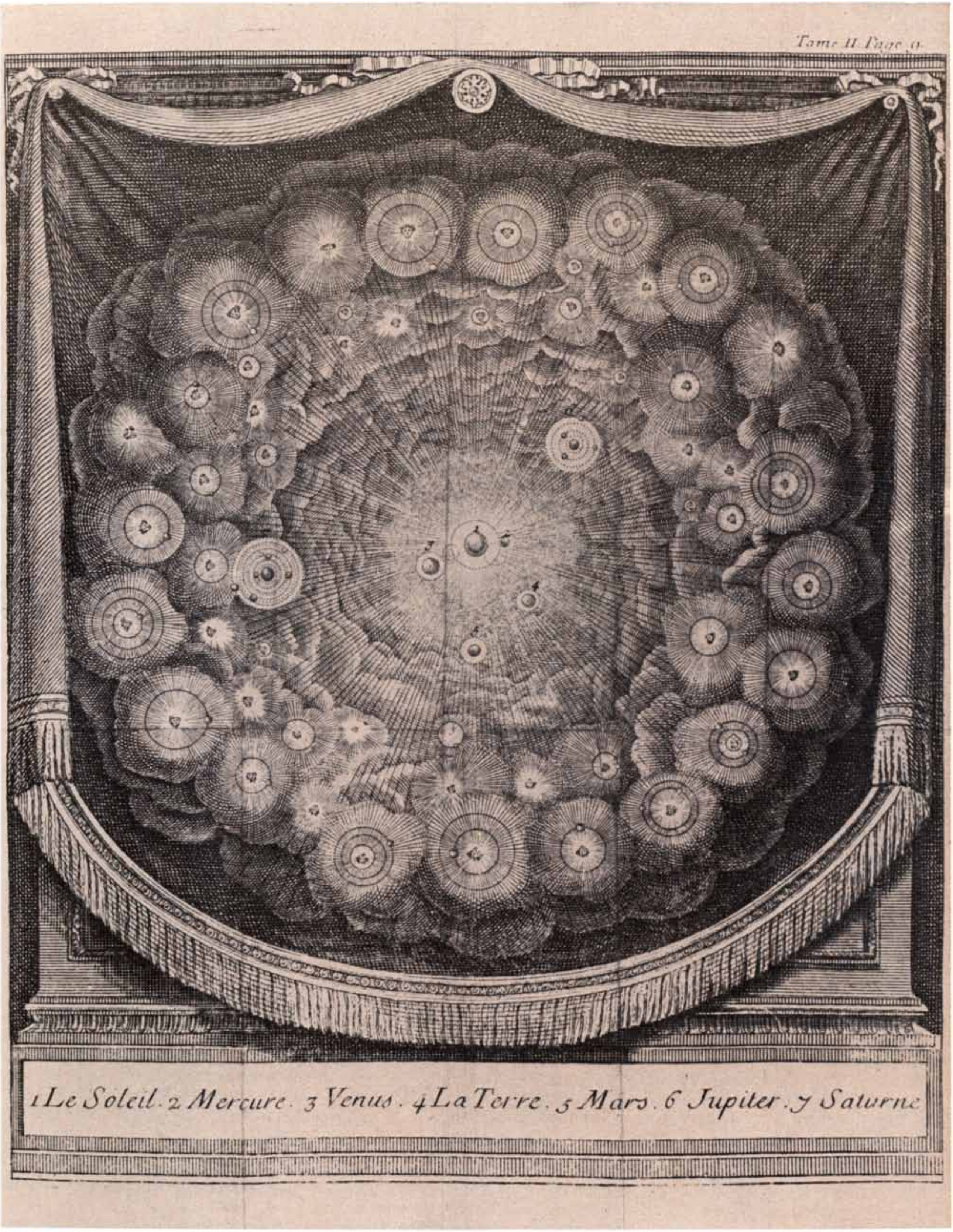


DIAGRAM OF A VORTEX, by which Descartes and others explained the orbital motion of the planets around the sun, is found in the notes of the poet Henry More for his *Philosophicall Poems,* published in 1647. In older theories of the universe the vortex was a hypothetical rotary movement of cosmic matter around a center or an axis, a movement that both allowed the solar system to form and continued to keep the planets moving in their orbits. More describes the illustration: "*CDBE* is that great Vortex, in which, and by which the Planets are carried from West to East, according to the order of *CDBE.* Let *A* be the Sun, the Center of this great Vortex." Point *F* marks the earth, which is circled by the moon. More's poem "Democritus Platonissans" praises the glories of Copernican system and has many astronomical references.



SOLAR SYSTEM portrayed in the frontispiece of the 1762 edition of Bernard Le Bovier de Fontenelle's *Entretiens sur la Pluralité des Mondes* (the first edition of which was published in 1686) combines old and new attitudes toward the picture of the universe. A soft, radiant version of the solar system is correctly drawn, to the extent that it was then known, on a draped theatrical curtain. The solar system is surrounded by stars, each of which is accompanied by its own system of planets; each star, however, is represented by the face of an angel.

The earth doth rest, heav'n move, and
fountains flow.
Nothing we see, but means our good,
As our delight, or as our treasure:
The whole is, either our cupboard of
food,
Or cabinet of pleasure.

Herbert also brings the new cosmos and man together in an almost cozy relationship, in keeping with his sense of the unity of all things. We are made to walk (or fly) with him as he imagines the work of the astronomer:

The fleet Astronomer can bore,
And thred the spheres with his
quick-piercing minde:
He views their stations, walks from
doore to doore,
Surveys, as if he had design'd
To make a purchase there: he sees their
dances,
And knoweth long before
Both their full-ey'd aspects, and secret
glances.

In "The Agonie" Herbert sees the power of the scientist to stride through the heavens:

Philosophers have measur'd
mountains,
Fathom'd the depths of seas, of states,
and kings,
Walk'd with a staffe to heav'n, and
traced fountains....

The same kind of imagination and exultation can be found in the religious poetry of Richard Crashaw, probably written in the 1640's. Crashaw, the most baroque of the English poets, seems as much at home in an outer world of stars and planets as Herbert is:

Drest in the glorious madnesse of a
Muse
Whose feet can walke the milky way....

Crashaw conveys a sense of space by describing the flight of the soul into a cloudy realm of the skies to meet the greatest of symbols, the name of Jesus:

Goe, SOUL, out of thy Self, and seek
for More.
Goe and request
Great NATURE for the KEY of her
huge Chest
Of Heavns, the self involving Sett of
Sphears
(Which dull mortality more Feeles
then heares)
Then rouse the nest
Of nimble ART, and traverse round
The Aiery Shop of soul-appeasing
Sound....

Crashaw establishes a world in his heavens that he imagines even as to the feel of the clouds and the sounds that he hears; music is omnipresent:

Come, nere to part,
NATURE and ART!
Come; and come strong,
To the conspiracy of our Spatious song.
Bring All the Powres of Praise
Your Provinces of well-united
WORLDS can raise;
Bring All your LUTES and HARPS of
HEAVN and EARTH;
What e're cooperates to The common
mirthe
Vessells of vocall Joyes,
Or You, more noble Architects of
Intellectuall Noise,
Cymballs of Heav'n, or Humane
spears,
Solliciters of SOULES or EARES....

Is Crashaw intimating here that sound is involved in the sensation of space and that we lose our spatial orientation when sound is absent? The discomfort of a soundproof room bears out Crashaw's intuition and Milton's more complex use of sound and imitations of it in *Paradise Lost.*

In "The Weeper" Crashaw celebrates Mary Magdalene, repentant sinner of the Gospels, whose tears become stars:

Heavens thy fair eyes be;
Heavens of ever-falling starres.
'Tis seed-time still with thee
And starres thou sow'st, whose
harvest dares
Promise the earth to counter shine
Whatever makes heavn's forhead fine.

In the fourth stanza her tears not only drop down but also fly up:

Upwards thou dost weep.
Heavn's bosome drinks the
gentle stream.
Where th'milky rivers creep,
Thine floates above; and is the cream.
Waters above th'Heavns, what they be
We'are taught best by thy TEARES
and thee.

And in the heavens, that indefinable stellar region, the tears become the wine for the souls of the dead who live there:

When some new bright Guest
Takes up among the starres a room,
And Heavn will make a feast,
Angels with crystall violls come
And draw from these full eyes of thine
Their master's Water: their own Wine.

Even as Crashaw was in nature's "aiery shop," Henry More, philosopher and poet of Cambridge, wrote that Cupid could hug the universe in his arms:

My mightie wings high stretch'd then
clapping light
I brush the starres and make them
shine more bright.

Then all the works of God with close
embrace
I dearly hug in my enlarged arms....

Cupid, here the god of Platonic love, is given powers that strain the imagination. Elsewhere More endowed spirits and angels, in which he earnestly believed, with similar attributes, including extension in space and "essential spissitude" (which can be defined as viscosity).

In a quite different vein More's *Democritus Platonissans* accurately describes the Copernican solar system with copious notes and diagrams to clarify his lines. The most informed and scientific of all the poets, More was unfortunately the least inspired; tedious and long-winded, he is often insuperably hard to read. One difficulty is that he wrote many of his poems in the ornate Spenserian stanza and employed archaic language that was outmoded even in the time of Spenser himself. Yet More must have realized that in order to be widely read by the literate public it was best to write in the respected medium of poetry, and that Copernicanism was more easily accepted in stanzas such as these:

The Centre of our world's the lively
light
Of the warm sunne, the visible Deity
Of this externall Temple. *Mercurie*
Next plac'd and warm'd more thor-
oughly by his rayes,
Right nimbly 'bout his golden head
doth fly:
Then *Venus* nothing slow about him
strayes
And next our *Earth* though seeming sad
full sprightly playes.

...so our worlds sunne
Becomes a starre elsewhere, and doth
derive
Joynt light with others, cheareth all
that won
In those dim duskish Orbs round other
suns that run.

How tantalizingly close the poet comes to the concept of gravity before Isaac Newton's discovery of it in 1682! He intuitively senses a force called then by many names: God, angels, vortices, the "primum mobile." More seems to have in mind a propulsion generated within the planets themselves; he combines, or rather bends, his knowledge of the way planets actually move to suit mythology: Mercury nimbly flies as he always flew as the messenger of the gods; Venus strays about the warm sun as she strayed in her amours, even though her orbit as a planet is one of the most circular. In the last two lines More specifically recognizes that man may not be alone in space. (The word "won" is to be read as "live" or "dwell.")

Less extravagant than Crashaw and less scientific than More were two modest clergyman-poets, Henry Vaughan and Thomas Traherne. In the course of their religious meditations they wrote verses that ranged far into the "Eternity" that Vaughan saw "the other night":

Like a great *Ring* of pure and endless
 light,
 All calm, as it was bright,
And round beneath it, Time in hours,
 days, years
 Driv'n by the spheres
Like a vast shadow mov'd, In which the
 world
 And all her train were hurl'd.

Both Vaughan and Traherne were Oxford men and therefore part of the small coterie of intellectuals of their day. Traherne specifically wrote that while he was at Oxford he studied "the secrets of nature with Albertus Magnus, the motions of the Heavens with Galileo, or the cosmography of the moon with Hevelius."

Almost every poem of Vaughan's *Silex Scintillans* (*Sparks from a Flint*), published in 1650 and 1655, is lighted by imagery of stars, those "fair, order'd lights" that "wind, and curle, and wink and smile," and by "the new worlds new, quickning Sun." (In the 17th century "world" meant an entire system, Ptolemaic or Copernican; "earth" meant only our planet.)

Traherne ranged further still. He imagined that the "Earth, the Seas, the Light, the Day, the Skies, / The Sun and Stars" were his as he speculated "never-endingly about eternity and infinity." He claims "new Worlds" as part of the realm of the God he is praising:

'Tis mean Ambition to desire
 A single World:
 To many I aspire,
 Tho one upon another hurl'd:
Nor will they all, if they be all
 confin'd,
 Delight my Mind.

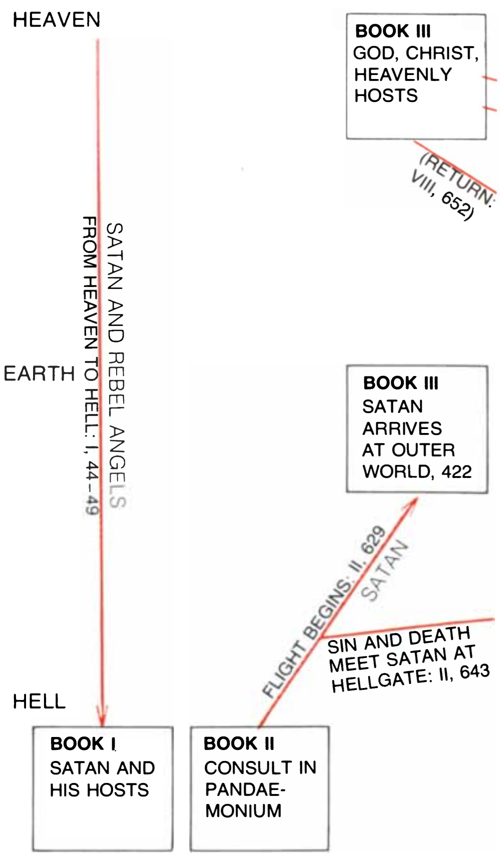
This busy, vast, enquiring Soul
 Brooks no Controul:
 'Tis very curious too.
Each one of all those Worlds must be
Enricht with infinit Variety
 And Worth; or 'twill not do.

Traherne's "Consummation" is an awkward but adventurous projection of infinity:

The Thoughts of Men appear
Freely to mov within a Sphere
 Of endless Reach; and run,
Tho in the Soul, beyond the Sun.
The Ground on which they acted be
Is unobserv'd Infinity.

 Traversing throu the Sky,
Tho here, beyond it far they fly:
 Abiding in the Mind
An endless Liberty they find:
Throu-out all Spaces can extend,
Nor ever meet or know an End.

Crashaw, Vaughan and Traherne were all lyric singers of space. John Milton was the epic voice. With *Paradise Lost* there comes into existence another—and perhaps the greatest—cosmic vision of the age. Later critics have worried because Milton was a "reluctant Copernican" and did not leave the old cosmology behind. The biblical Ptolemaic scheme is his framework. One can see why: Milton needed the old system to assert his moral. Man had to be central in a central earth so that he could be the focus of the scheme of things. Moreover, because of his God-given freedom of choice, he was responsible for the good and the evil on earth. Nevertheless, Milton's vision of the cosmos is unconfined in space and time. He projects the universe of his epic through violent contrasts of light and dark, in crescendos and decrescendos of sound, through



FLIGHTS IN "PARADISE LOST" carry the action across vast reaches of space and both

action, through flight backward in time as well as forward. The entire epic represented by *Paradise Lost* can be outlined in a succession of flights across a three-sphere universe consisting of heaven, earth and hell.

Satan is the first to experience the vastness of the universe. As he looks out from the gates of hell before beginning his flight to earth, even he is terrified by what he sees. Accompanied by Sin, his paramour, and by Death, his child, he gazes out into chaos:

Before thir eyes in sudden view appear
The secrets of the hoarie deep, a dark
Illimitable Ocean without bound,
Without dimension, where length, breadth, and highth,
And time and place are lost....

With angels' weightlessness, he resumes his flight. But even he is subject to air pockets:

At last his Sail-broad Vans
He spreads for flight, and in the surging smoak
Uplifted spurns the ground, thence many a League
As in a cloudy Chair ascending rides
Audacious, but that seat soon failing, meets
A vast vacuitie: all unawares
Fluttring his pennons vain plumb down he drops
Ten thousand fadom deep, and to this hour
Down had been falling, had not by ill chance
The strong rebuff of som tumultuous cloud
Instinct with Fire and Nitre hurried him
As many miles aloft....

Soon he sees "this pendant world" in the distance—vulnerable, defenseless, "a Starr of smallest Magnitude close by the Moon."

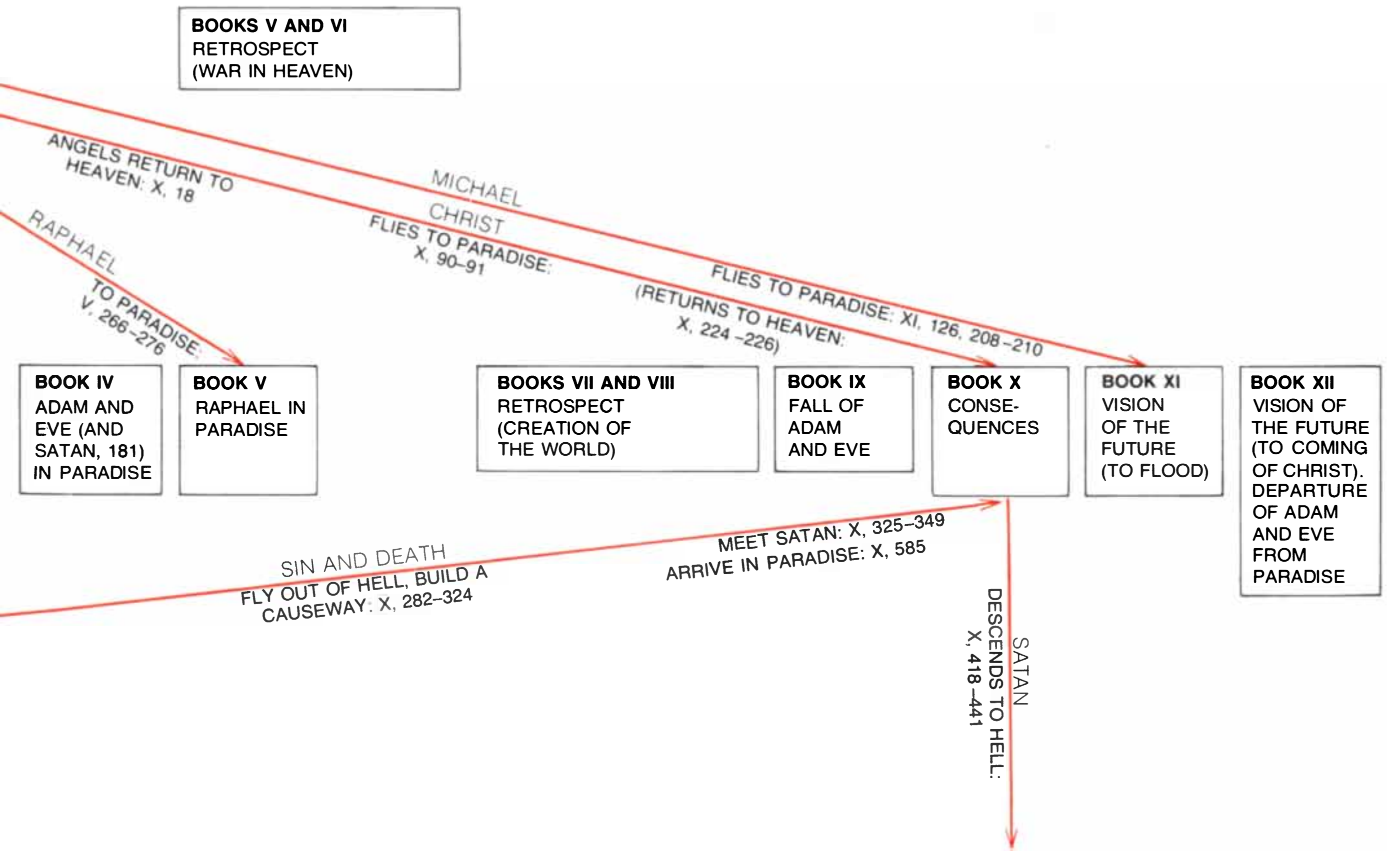
His flight toward it is difficult. He labors:

So eagerly the fiend
Ore bog or steep, through strait, rough, dense, or rare,
With head, hands, wings or feet pursues his way,
And swims or sinks, or wades, or creeps, or flyes....

Then he "springs upward like a Pyramid of fire" and finally, with "Shrouds and Tackle torn," lands on earth. Satan as a launching rocket and a floating astronaut, and the earth as we have recently seen it from the moon, are all imaginable from Milton's lines.

As a counteraction to Satan's flight Raphael, the sociable angel, flies from heaven to earth to warn Adam and Eve of Satan's coming. In a complex play with the sequence of time Raphael takes Adam and Eve through the history of the universe before their own creation. The battle in heaven is projected before them: Satan and his Olympians align themselves against God and the angels and archangels. Mountains are hurled against mountains; heaven seems to return to the chaos below it. But Satan and his rebellious angels are defeated and are hurled out into space down to hell. To replace Satan and his followers the earth is created. From the distance of a star, through the vast sweep and action of Milton's lines, we watch with Adam and Eve as the universe is created. The earth was formed on the third day and the sun, the moon and the stars on the fourth:

For of Celestial Bodies first the Sun
A mightie Sphear he fram'd, unlightsom first,
Though of Ethereal Mould: then form'd the Moon
Globose, and every magnitude of Starrs,



backward and forward in time. Here the flights of Satan, Christ and angels between heaven, earth and hell described in each of the 12 books are diagrammed. Pertinent passages are identified by book and line number. Illustration is based on work of Mary Hoskinson.

And sowd with Starrs the Heav'n thick
as a field. . . .

There is a rising crescendo of action and sound up to the seventh day, when the completion of the universe is celebrated. The music of the spheres—of the stars, of the planets, of the angels—rings, resounds and echoes throughout the new creation.

After the vision we are returned to Adam and Eve's present. Inevitably they are corrupted. As a result of their symbolic act of eating the apple from the tree of knowledge the entire universe changes convulsively. In a rearrangement of the cosmos the action is speeded up in a chaotic series of fights between heaven, hell and earth. The last scenes of the epic are earth-centered. Adam and Eve, now mere human beings, are expelled from the Garden of Eden. The choice of good or evil is up to them and their descendants. The end of the epic is overwhelming. The visions of space and time, the cosmic flights are over. We are landed squarely on earth.

The intoxication with space that appears in England's poetry set painters of the baroque period on equally ambitious voyages beyond the sky. Guercino (1591–1666) and others show action in space and time that could only have occurred to them after the confines of the old model of the cosmos had been split open. In the painting "Aurora" Guercino has gods, chariots and horses thundering across the sky in an immense ceiling painting that lifts the viewer out of his dimensions and compels him to join the flight of the gods above him. In "Divine Wisdom," painted by Andrea Sacchi at the Barberini Palace in Rome between 1629 and 1633, the earth floats in space. In "Adoration of the Name of Jesus," painted by Giovanni Battista Gaulli ("Il Baciccio") in a church in Rome between 1672 and 1685 angels and sacred personages fly upward in an explosion of wings and draperies.

It is remarkable how many artists in the three centuries since Milton's death have been inspired by *Paradise Lost*—more, perhaps, than by any other work except for Dante's *Divine Comedy*. Almost all of them, including the 19th-century illustrators Gustave Doré and John Martin, try to give their impression of the vastness of the poem. In our own day Milton's descriptions have even been translated into film: Sergei Eisenstein modeled the battle scenes of *Alexander Nevsky* on Milton's war in heaven. John Collier has attempted to present the action of the poem in *Milton's Paradise Lost: Screenplay for the Cinema of the Mind*.

After 1660, with the founding of the Royal Society of London as an arbiter of both science and literature, there came a change in attitude toward poets and poetry. Thomas Sprat, the historian of the Royal Society, proclaimed that all writing leaning heavily on metaphorical language—the language of "fancy" and imagination—could be a barrier to truth. He advocated a "close, naked, natural way of speaking; positive expressions, clear senses; a native easiness; bringing all things . . . near Mathematical plainness." He placed "the language of Artizans, Countrymen, and Merchants, before that of Wits, or Scholars." By "wits" Sprat particularly meant poets, with their delight in analogy as a way of describing relations between man and the cosmos. His attack suggests he was afraid of the poet's influence over men's minds—"bewitching," he called it. His diatribe carries all the fervor of an attack on the communications media today. By the end of the 17th century the poet could no longer write with quite the same belief in himself as a prophet and a seer into the nature of things; intuition had increasingly to give way to the revolution in scientific knowledge that was to follow.

These old poets, to use the words of Sir Thomas Browne, were "true amphibia" that lived in "divided and distinguished worlds." What is always renewing in their poems is their sense of the marvelous. There is a freshness in Andrew Marvell's wonder at "Stars [that] shew lovely in the Night, / But as tney seem the Tears of Light"; we find it also in Traherne's "On Leaping over the Moon," where he sees new worlds mirrored in a pool of water. To Traherne the entire universe was a world of treasure and man was its temple of infinity.

To find such poetry, which transcends time and knowledge, one has to go back to before the 1660's. Yet the relatedness of all things that the poet celebrated was no mere projection of his "fancy." Today the ancient elements—fire, air, water and earth—have yielded to the *u* and *d* quarks, the electron and the electron neutrino as the components of all matter. "These four particles," writes Sheldon Lee Glashow, "are the only ones needed to construct the world; they are sufficient to build all atoms and molecules, and even to keep the sun and other stars shining" [see "Quarks with Color and Flavor"; SCIENTIFIC AMERICAN, October, 1975]. In principle the poet's intuition was right.

Even more important, to understand the universe opened up beyond the reach of our senses and of our common sense, and to make that universe our own, we still rely on the poet's devices of the analogy, the simile, the hyperbole. The animistic, anthropomorphic world invoked by poetic imagery helps to bridge the gap between scientific discovery and the layman's comprehension. We continue to learn about the rest of the world through reference to ourselves and our common everyday experience.

SCIENCE/SCOPE

Meteorologists will be able to paint a three-dimensional picture of the earth's cloud cover -- and improve long-range weather forecasting -- when a new instrument, aboard geostationary meteorological satellites, is launched around 1980. The instrument, to be built by Santa Barbara Research Center, a Hughes subsidiary, is called VAS (Visible Infrared Spin-Scan Radiometer Atmospheric Sounder).

The VAS will take vertical soundings of the earth's atmosphere, examining the water vapor and carbon dioxide absorption bands, in order to obtain data on temperature and humidity at various altitudes. This vertical profile is then compared to the measured temperature of adjacent cloud tops to determine the altitude of the clouds. By observing the direction and speed of these clouds, meteorologists can determine wind movement at various heights, adding this information to the two-dimensional picture obtained by the earlier VISSRs.

This will be the first time that vertical soundings will be made from a geostationary satellite, so the VAS will provide previously unattainable information on atmospheric circulation patterns, a vital part of weather forecasting.

The invisible fabric that weaves diverse and complex hardware into today's major weapon systems is software, which is the programming of computers within these systems. More than 25 years ago -- that's even before software was called software -- the Hughes initial entry into the specialized technology of software was an airborne, digital, fire-control system for the "Century" series of interceptor aircraft. As systems became more sophisticated to meet growing threats, Hughes software teams were formed with specialists in programming the fire-control systems.

Today, the nearly one thousand team members provide software for such diverse programs as the Navy's AWG-9 fire-control system, the Air Force's F-15 airborne radar, the Army's AN/TPQ-36 and -37 mortar and artillery-locating radars, SURTASS antisubmarine-warfare program, the NATO NADGE air-defense systems, and JTIDS (AN/ARC 191), a joint service program to provide a secure, real-time communication network.

Hughes needs communications-satellite engineers, at all levels of experience, to design and develop advanced digital-communications hardware. There are opportunities in circuit, logic, and unit design for phase-lock loop demodulators and bit synchronizers; spread-spectrum and PSK demodulators; DFT- and FET-hardware design; and microprocessor control design, primarily below 100 MHz. Also openings for microelectronic design engineers in logic and circuit design and layout of custom CMOS/SOS microcircuits, for high-reliability space applications, advanced CCD memories, signal-processing devices, and tradeoffs of CMOS/SOS, ECL, I^2L, PMOS, TTL, CCD, and GaAs technologies. US citizenship and a degree from an accredited institution are required. Please send resume to Don H. Haycock, Hughes Aircraft Company, PO Box 92919, Los Angeles, California 90009. An equal opportunity M/F/HC employer.

Reduced energy consumption and extended equipment life will result from a new facility-management system being developed by Hughes for installation at the Air Force's Arnold Engineering Development Center. The system will monitor and control most of the heating, ventilating, and air-conditioning equipment in the Center's 42 buildings. The system can be programmed to shut down nonessential operations automatically during periods of peak-power requirements.

Data is transferred between remote terminals and a computer-controlled central station via time-division multiplexing. Other functions, such as closed-circuit TV, can be added. It is estimated the system will result in savings of $200,000 annually in energy and labor costs and will pay for itself in four years.

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MATHEMATICAL GAMES

The concept of negative numbers and the difficulty of grasping it

by Martin Gardner

Inhabitants of Nega look surprisingly like us.
Their students seek a minus grade, they grumble at a plus.
In minus-fours the golfer walks, he never adds his score.
Meanwhile, non-minussed is his wife by prices at the store.

—IRVING E. FANG,
"A Tale of Star-crossed Lovers"

When a child learns to talk, the names of the first few positive integers are almost as essential to his vocabulary as "dog," "cat" and "bird." Our primeval ancestors must have had a parallel experience. The counting numbers, sometimes called the natural numbers, were surely the first to be useful enough to require names. Today mathematicians apply the word "number" to hundreds of strange abstract beasts that are far removed from counting.

The first small step in enlarging the meaning of "number" was the acceptance of fractions as numbers. Although many things in the world are not commonly experienced as fractions (stars, cows, rivers and so on), it is easy to grasp the meaning of half an apple or a third of 12 sheep. But the next step, the acceptance of negative numbers, was so formidable that it was not until the 17th century that mathematicians began to feel truly comfortable about it. Many people are still uneasy with it, as is indicated by W. H. Auden's report of a jingle he was taught in school:

Minus times minus equals plus.
The reason for this we need not discuss.

One must distinguish negative numbers from subtraction. A child or an uneducated herdsman has no difficulty taking six cows from 10 cows. A "negative cow," however, is harder to imagine than a ghost cow. A ghost cow has at least some kind of reality, but a negative cow is less real than no cow. A cow from a cow leaves nothing, but adding a negative cow to a positive cow, causing both to vanish like a particle meeting its antiparticle, seems as ridiculous as the old joke about the individual whose personality was so negative that when he walked into a party, the guests would look around and ask, "Who left?"

That was how the ancient Greeks felt about negative numbers. They loved geometry and liked to think of mathematical entities as things they could diagram. "Numbers" were the counting numbers and the positive integral fractions that could be modeled with pebbles or spots on a slate. The Greeks' primitive algebra had no zero and no negative quantities. They were even reluctant to call 1 a number because, as Aristotle put it, numbers measure pluralities, and 1 is the measuring unit, not a plurality.

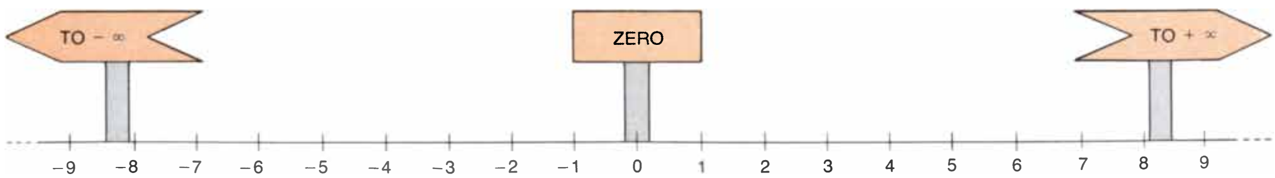
It is important to realize that this attitude was to a large extent a matter of linguistic preference. Greek mathematicians knew that $(10-4)(8-2)$ equals $(10\times 8)-(4\times 8)-(2\times 10)+(2\times 4)$. To recognize such an equality is to accept implicitly what later was called the law of signs: the product of any two numbers with like signs is positive, the product of any two numbers with unlike signs is negative. It was just that the Greeks preferred not to call $-n$ a number. To them it was no more than a symbol for something to be taken away. You can take two apples from 10 apples, but taking 10 apples from two apples struck them as senseless. They knew that $4x+20=4$ gives x a value of -4, but they refused to write such an equation because its solution was "not a number." For the same reason $-\sqrt{n}$ was not recognized as a legitimate square root of n.

It is hard to know exactly how the earlier Babylonians regarded negative quantities, but they seem to have been more comfortable with them than the Greeks were. Chinese mathematicians before our era calculated rapidly with bamboo counting rods, using red rods for positive numbers (*cheng*) and black rods for negative numbers (*fu*). The same colors were later used for positive and negative written numerals. *Nine Chapters on the Mathematical Art,* a famous work of the Han period (roughly 200 B.C. to A.D. 200), explains the rod procedures and is believed to contain the first appearance in print of negative numbers as such. It does not, however, recognize negative roots or the law of signs.

A systematic algebra using zero and negative numbers did not develop until the seventh century, when Hindu mathematicians began to employ negative values for problems concerning credit and debts. Not only were they the first to use zero in a modern way but also they wrote equations in which negative numbers were symbolized by a dot or a tiny circle above the number. They explicitly formulated the law of signs and recognized that every positive number has two square roots, one of them positive and one negative.

Most Renaissance mathematicians in Europe, following the Greek tradition, viewed negative quantities with suspicion. Here again one must remember that it was more a matter of language preference than a failure to understand. Renaissance algebraists knew perfectly well how to manipulate negative roots; they just called them "fictitious roots." They knew perfectly well how to solve equations with negative numbers; they just avoided applying the word "number" to quantities less than zero.

By the 17th century a few bold mathematicians had altered their language to include negative numbers as legitimate numbers, but the practice continued to meet with resistance, sometimes from prominent mathematicians. Descartes spoke of negative roots as "false roots," and Pascal thought it nonsense to call anything less than zero a number. Pascal's friend Antoine Arnauld proved the



The number line for integers

A Positive Reminder

by J. A. Lindon

A carpenter named Charlie Bratticks,
Who had a taste for mathematics,
One summer Tuesday, just for fun,
Made a wooden cube side minus one.

Though this to you may well seem wrong,
He made it *minus* one foot long,
Which meant (I hope your brains aren't frothing)
Its length was one foot less than nothing.

In width the same (you're not asleep?)
And likewise minus one foot deep;
Giving, when multiplied (be solemn!),
Minus one cubic foot of volume.

With sweating brow this cube he sawed
Through areas of solid board;
For though each cut had minus length,
Minus *times* minus sapped his strength.

A second cube he made, but thus:
This time each one foot length was plus;
Meaning of course that here one put
For volume: *plus* one cubic foot.

So now he had, just for his sins,
Two cubes as like as deviant twins;
And feeling one should know the worst,
He placed the second in the first.

One plus, one minus—there's no doubt
The edges simply cancelled out;
So did the volume, nothing gained;
Only the surfaces remained.

Well may you open wide your eyes,
For these were now of double size,
On something which, thanks to his skill,
Took up no room and measured nil.

From solid ebony he'd cut
These bulky cubic objects, but
All that remained was now a thin
Black sharply-angled sort of skin

Of twelve square feet—which though not small,
Weighed nothing, filled no space at all.
It stands there yet on Charlie's floor;
He can't think what to use it for!

On the mystery of 12 square feet

absurdity of negative values as follows:

The law of signs forces one to say that $-1/1 = 1/-1$. If this is taken as an equality between two ratios, we must assert that a smaller number is to a greater one as a greater number is to a smaller one. This seeming paradox, as Morris Kline points out in *Mathematical Thought from Ancient to Modern Times,* was much discussed by Renaissance mathematicians. Leibniz agreed that it was hard to resolve, but he defended negative numbers as useful symbols because they make possible correct calculations.

Some leading mathematicians of the 17th and 18th centuries—John Wallis and Leonhard Euler, to name two—accepted negative numbers but believed they were greater than infinity. Why? Because $a/0 = \infty$. Therefore if we divide a by a number smaller than zero, say -100, must we not produce a negative quotient that exceeds infinity?

Symbols for addition and subtraction varied considerably during the Renaissance. Today's familiar plus and minus signs were first used in 15th-century Germany as warehouse marks. They indicated when a container held something that weighed over or under a standard weight. By the early 16th century German and Dutch algebraists were using $+$ and $-$ as operation signs, and the practice soon spread to England. Robert Recorde, a physician to Edward VI and Queen Mary, wrote a popular arithmetic in 1541 that was the first in English to use plus and minus signs, although not as operations. "Thys figure +, which betokeneth too much, as this lyne —, plaine without a cross lyne, betokeneth too lyttle" was how he explained them. A later book by Recorde was the first in England to use the modern sign for equality. "I will sette as I doe often in woorke use, a pair of paralleles . . . thus: ═══, because noe 2 thynges, can be moare equalle."

In the 18th century the algebraic use of negative numbers, identified by the minus mark, became common around the world. Nevertheless, most mathematicians remained discomfited. Their books included long justifications for the law of signs, and some authors went to extreme lengths rearranging equations to avoid multiplying two negative numbers. Here is a passage from *Dissertation on the Use of the Negative Sign in Algebra* (1758), by Baron Francis Masères, a British barrister who served as attorney general in Quebec:

"A single quantity can never be . . . considered as either affirmative or negative; for if any single quantity, as *b,* is marked either with the sign $+$ or with the sign $-$, without assigning some other quantity, as *a,* to which it is to be added, or from which it is to be subtracted, the mark will have no meaning or signification: thus if it be said that the square of -5 . . . is equal to $+25$, such an assertion must either signify no more than that 5 times 5 is equal to 25 without any regard to the signs, or it must be mere nonsense and unintelligible jargon."

The passage is quoted by Augustus De Morgan in *A Budget of Paradoxes.* Masères, De Morgan tells us, was such an honest lawyer that he was not able to bear seeing his client victorious if he thought him guilty. As a result, writes De Morgan, Masères's business gradually fell off.

A few pages earlier De Morgan makes a blistering attack on *The Principles of Algebra,* by William Frend, a former clergyman who happened to be his father-in-law. (Frend's noisy banishment from Cambridge for his Unitarian views became a cause célèbre, passionately championed by Samuel Taylor Coleridge and Joseph Priestley.) Frend's two-volume work was probably the most ambitious algebra textbook ever written in which zero and all negative numbers were as unwelcome as Frend was at Cambridge.

De Morgan reprints in full Frend's hilarious burlesque of Rabelais, in which Pantagruel gives a wild lecture on the uselessness of zero. A plaintive footnote quotes Mrs. De Morgan: "[My father's] mental clearness and directness may have caused his mathematical heresy, the rejection of the use of negative quantities in algebraical operations; and it is probable that he thus deprived himself of an instrument of work, the use of which might have led him to greater eminence in the higher branches."

How can one do algebra without negative numbers? First one must avoid any equation that leads to a negative number of real objects or assigns negative magnitudes to them. Even when an equation leads to a correct positive solution, it must be written so as to avoid a negative value for an unknown. For example: When is a 29-year-old mother twice as old as her 16-year-old daughter? We might write the problem as $29 + x = 2(16 + x)$, then discover, perhaps to our surprise, that $x = -3$. This result leads to the correct answer: The mother *was* twice as old as her daughter when the mother was 26 and the daughter was 13. An 18th-century algebraist, if he was repelled by negative numbers, would have avoided the -3 by rewriting the equation: $29 - x = 2(16 - x)$. This arrangement gives x the acceptable value of 3, which of course leads to the same answer as before.

In past centuries, as it is today in beginning algebra classes, the main stumbling block to the acceptance of negative numbers was "seeing" how the product of two negative numbers can be positive. Positive times positive offers no difficulty. Put three pairs of oranges in an empty bowl and the bowl will contain six oranges. Positive times negative begins to get mysterious but is not hard to understand if you grant the abstract reality of a negative orange. Put three pairs of negative oranges in the bowl and you have six negative oranges. But what on earth does it mean to multiply two negative oranges by -3? You have two ghostly oranges to start with, all less than nothing, and then you do something negative to them. Where do the six genuine oranges come from? They seem to appear in the bowl as a result of magic.

Trying to explain it by walking the number line, as is shown in the illustration on the preceding page, does not get very far with beginning students. It is easy to identify positive integers with unit marks to the right of zero and negative integers with unit marks to the left. Addition is movement to the right and subtraction is movement to the left. To multiply 2 by 3 we go two units to the right and do this three times to arrive at 6. To multiply -2 by 3 we walk two units to the left and do this three times to arrive at -6. But what about -2 times -3? What paranormal force transports us abruptly from the left side of 0 to 6 on the right?

It is easy to forgive mathematicians of earlier centuries for regarding this concept as being preposterous. Indeed, the process was not fully understood until such abstract structures as groups, rings and fields were carefully defined. This is not the place to explain them, and so I content myself with pointing out that when mathematicians found it desirable to enlarge the concept of number to take in zero and negative numbers, they wanted the new numbers to behave as much like the old ones as possible.

One of the fundamental axioms of the old arithmetic is the distributive law, which states that $a(b + c) = ab + ac$; for example, $2(3 + 4) = (2 \times 3) + (2 \times 4)$. Change the 2 and 3 to negative numbers and the equality will still hold only if we adopt the rule that the product of two negative numbers is positive. If the product were negative, the equation would reduce to $-2 = -14$, a contradiction. In modern terms, the integers form a "ring" that is closed with respect to addition, subtraction and multiplication. This provision means that no matter how we add, subtract or multiply integers, whatever their sign, the result is always an integer. All the old laws of arithmetic for positive integers still hold, and we never encounter a contradiction. (We cannot always divide because we might get a fraction, and fractions are not elements of the ring.)

It is therefore not correct to say mathematicians can "prove" that the product of two negatives is a positive. It is rather a case of agreeing on rules that allow the negative numbers to obey all the old rules for counting numbers. If integral fractions are also included, the ring enlarges to a "field" that is closed under all four arithmetic operations.

Although there is no "proof" that $-2 \times -3 = 6$, it is easy to think of ways in which the law of signs applies to real situations. Indeed, it applies to all situations involving numbers on a scale that has two opposite directions or senses: east and west, up and down (as on a thermometer), forward and backward in time (or clockwise and counterclockwise on a clock), profit and loss, and hundreds of others. It is because of these applications that the "signed numbers" are sometimes called "directed numbers."

In applying the law of signs to these examples we must always distinguish the quantities from the operations performed on them. The distinction is particularly necessary when we consider the multiplication of a signed quantity by a negative number. It is easy to understand what it means to take a positive or a negative quantity n times, but what does it mean to take it $-n$ times? The clearest way to think about this mystifying operation is to break it into two parts:

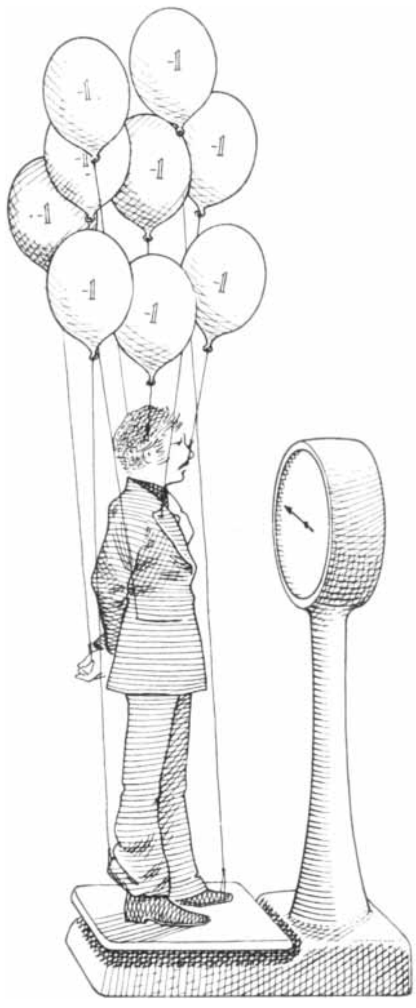
1. Duplicate the quantity n times.
2. Convert the result to its inverse with respect to zero. In other words, change the sign.

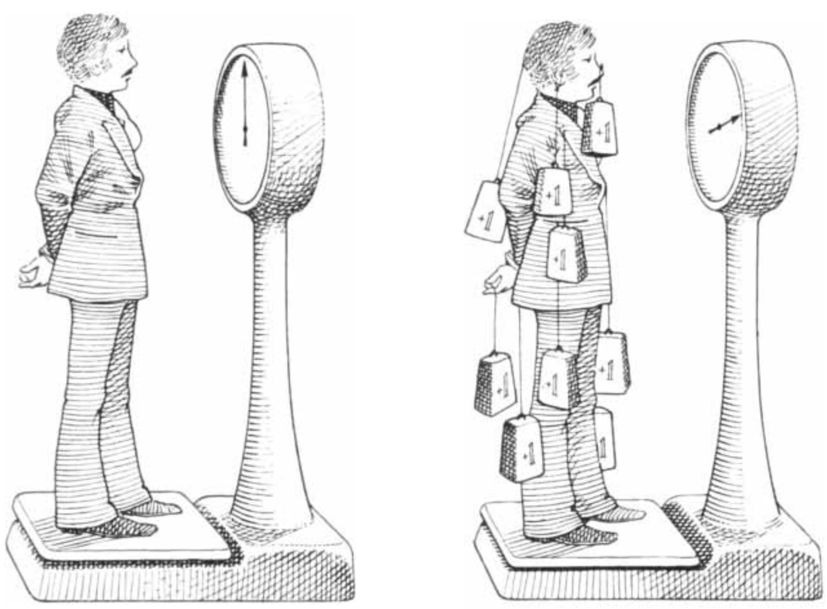
On the number line the second step is the same as reflecting a spot by a mirror on the zero mark. Imagine a bug at -2. To multiply its position by 3 there is no difficulty. We simply duplicate -2 three times to carry the bug to -6. But if the bug is at 2 and we wish to multiply by -3, our operation is to duplicate 2 three times, putting the bug at 6, and then invert. This procedure transports the bug to the mirror-image spot at -6. If the bug is at -2, multiplication by -3 operates the same way. We duplicate -2 three times, taking the bug to -6, and then inversion carries it to 6.

This may look like sorcery on the number line, but when we apply the procedure to many other situations, it seems quite normal. For example, suppose a man loses \$10 a day gambling. The future is defined as being positive and the past as being negative. Three days from now he will have lost \$30 ($3 \times -10 = -30$). Three days ago he had \$30 more than he has today ($-3 \times -10 = 30$). Equivalent situations arise on any directed scale. If water is sinking in a tank at a rate of three centimeters per minute, the level two minutes ago was $-3 \times -2 = 6$ centimeters higher. If the bug crawls west on the number line three centimeters per second, then two seconds ago it was $-3 \times -2 = 6$ centimeters east of its present position.

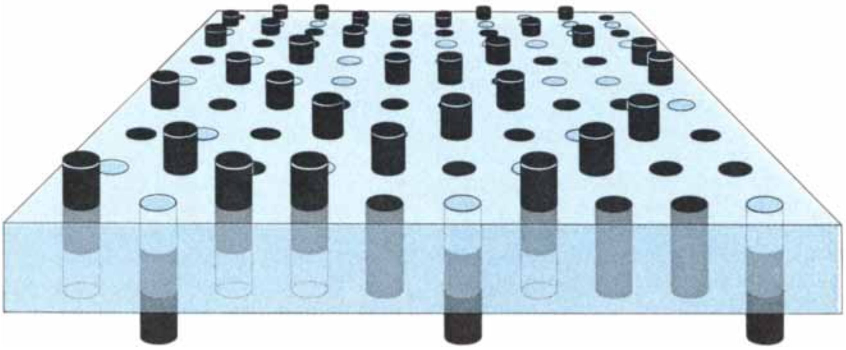
The most familiar property of objects that lends itself to negative magnitudes is weight. Add one-gram weights to your pockets and you are heavier. Attach helium-filled balloons to your body, each lifting with a force of one gram, and you are lighter. Remove three pairs of balloons and your weight increases by $-2 \times -3 = 6$ grams.

"Imagine a town where good people





A model for the law of signs



The pegboard that keeps track of signs

are moving in and out," wrote Roy Dubisch (*The Mathematics Teacher,* December, 1971), "and bad people are also moving in and out. Obviously, a good person is + and a bad person −. Equally obvious, moving in is + and moving out is −. Still further, it is evident that a good person moving into town is a + for the town; a good person leaving town is a −; a bad person moving into town is a −; and, finally, a bad person leaving town is a +." If three pairs of bad people move out, the town gains $-2 \times -3 = 6$ points. One can model the situation with poker chips of two colors and a spot to represent the town.

Other models for teaching children the operations that can be done on the ring of integers have been proposed. Here is one of my own, so simple that others have surely thought of it before. It consists of a square board one centimeter thick in which 100 holes have been drilled in a square array. Each hole is fitted with a peg one centimeter long. The peg can be in one of three positions: flush with the board (0), projecting upward half a centimeter (+1) or projecting downward half a centimeter (−1). If all the pegs are flush, the board is in state 0. If k pegs are up, it is in state k; if k pegs are down, it is in state $-k$.

To add n to the state of the board, push n pegs up, always pushing down pegs up (if there are any down pegs) before moving to flush pegs. To subtract n from the board's state, push n pegs down, taking first the up pegs (if there are any) before moving to flush pegs.

To multiply the state of the board by n, duplicate the state n times. If the state is 0, there is nothing to do. If k pegs are up, push up $n - 1$ more sets of k pegs. If k pegs are down, push down $n - 1$ more sets of k pegs. To multiply the board's state by $-n$, first multiply by n (as above) and then turn the board over.

A model that is probably easier to make is a board with little switches that can be in the up (+), middle (0) or down (−1) position. In this case multiplying by a negative number ends with rotating the board 180 degrees.

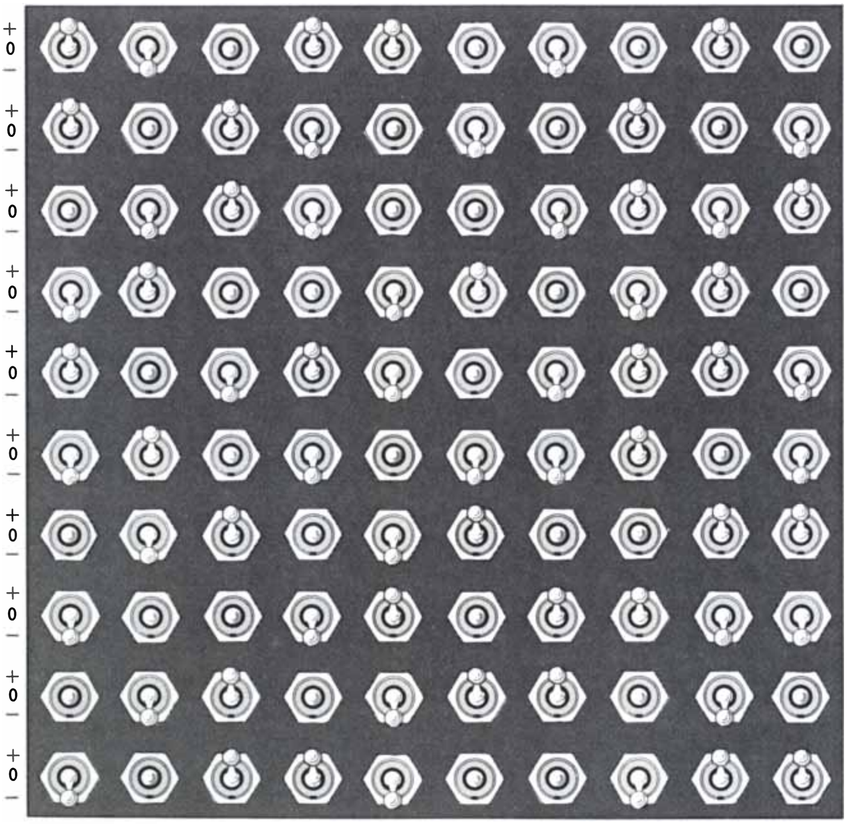
If Aristotle were alive today and had 20 years to study modern algebra, he might still prefer to use "number" only for the counting numbers greater than 1. (There is a sense in which all "artificial numbers" are no more than constructions of the natural numbers.) This is one of those arguments over words that get nowhere. The point is that rings and fields, in which every element has its inverse or negative twin, are applicable to an enormous variety of natural objects and phenomena.

We may get into serious trouble trying to apply negative numbers and the law of signs to cubes and other "things" in the real world, as in J. A. Lindon's poem on page 132, but sometimes the application is unexpectedly appropriate. Ignoring radiation, the pegboard is not a bad model of P. A. M. Dirac's famous theory about particles and antiparticles, a theory that predicted the existence of the positron!

One of last month's questions concerned the game of three men, three red hats and two black hats. The men are seated in chairs so that A sees B and C, B sees only C and C sees no one. An umpire puts any three hats (from the set of five) on their heads. Each man is asked (in the order A, B, C) if he knows his hat's color. Will one of them always answer yes?

The answer is yes. An analysis of all color combinations will show that if the *ABC* order of hats is *RRR, RBR, BRR* or *BBR,* then C will say yes. If the order is *RRB* or *BRB,* then B and C will say yes. If it is *RBB,* all three will say yes. This analysis generalizes to n men with n red and $n - 1$ black hats. Consider $n = 4$. D, the "blind" man, reasons: "If my hat is black, the other three men will see it and know that only two black hats are left for them. The case will then be the same as the preceding one, which has been solved. If no one says yes, it can only be because my hat is red, and so I will say yes." And so on for any n. The first person to say yes is always the first one asked wearing a red hat and seeing no red hat.

John Erbland, a mathematics student at Northeastern University, thought of an amusing variant. Suppose there are n men, $n - 1$ black hats and only one red



Switchboard model for the law of signs hat. Conditions are the same as before. Will the man with the red hat always say yes? If not, at what positions will he know the color of his hat? I shall discuss this problem next month.

The game of consecutive numbers on the foreheads of two men is analyzed as follows. Let H stand for the man with the higher number, L for the man with the lower one and Qn for the question number.

Suppose the numbers are 1 and 2. If H is asked first, he answers yes to $Q1$. If L is asked first, he says no. Then H, seeing the 1, says yes to $Q2$.

Suppose the numbers are 2 and 3. If H is asked first, he says no. L also says no. His answer proves that he does not see 1 on H, and so H knows that he is 3 and says yes to $Q3$. If L is asked first, he says no. As before, this answer tells H that his number is 3, and so he says yes to $Q2$.

Suppose the numbers are 3 and 4. If H is asked first, he says no. L also says no. H can now reason: "If I am 2, the game is reduced to the preceding case of 2, 3, with L asked first. Therefore L would say yes to $Q2$. Since L said no, it proves I am 4." Therefore H says yes to $Q3$. If L is asked first, he says no. H says no to $Q2$, which reduces the situation to the previous case, as before. L's no to $Q3$ tells H that he is 4, and so he says yes to $Q4$.

Continuing in this way, the situation always reduces to a previously solved case. Let n be the higher number. H always wins. If he is asked first, he wins on $Q(n-1)$ if n is even and on Qn if n is odd. If he is asked second, he wins on Qn if n is even and on $Q(n-1)$ if n is odd. Note the curious fact that if the rule is that a player answer yes only if he knows he has the *lower* number, the game never ends!

Now for the seeming paradox. In the case of three men, all with red hats, it is true that both B and C know in advance that A will say no. But—and this is the easily overlooked and crucial point—C does not know before the first question is asked that B knows that A will answer no. Before the questioning starts, for all C knows his own hat may be black. If that is the case, B has no way of knowing whether A will say yes or no. Not until A says no does C know that B knew in advance of the question that A had to say no. Therefore the first question does add new information that is essential to C's reasoning even though C knows in advance how A will answer.

Once this relation is understood it is not hard to see how the paradox is resolved for the Gale and Conway games. Suppose you are a player in Gale's game. Each new "No" in a game of arbitrary length gives you necessary new information in the general form of "I now know that you know that I know . . . that you don't know my number." It is the same for Conway's game. Each "No" provides each player with similar information about what the others know.

BOOKS

Stanislaw Ulam, unusual abodes, the earth from above and the history of U.S. farming

by Philip Morrison

ADVENTURES OF A MATHEMATICIAN, by S. M. Ulam. Charles Scribner's Sons ($14.95). In 1949 radioactivity from the first Russian fission-bomb test contaminated the filters of an Air Force reconnaissance plane. Soon the theorists were set hard at work at Los Alamos and at Princeton: Could a fusion bomb be made? At Los Alamos "we started to work each day for four to six hours with slide rule, pencil, and paper." At Princeton the brand-new computer MANIAC was trying to catch up with the Los Alamos mathematician pair, the witty Stan Ulam and his taciturn partner of prewar days, Cornelius Everett. (Everett "used to say, 'I never make mistakes' and this was true...." Once when Edward Teller maintained that Everett had made an error of a factor of 10^4, Everett became annoyed; eventually "Edward had to admit that it was he who was at fault.") Nothing worked; the device on paper would not ignite. Enrico Fermi and Ulam next showed that the paper explosion would not spread, and John von Neumann soon reported MANIAC's concurrence: "Icicles are forming." After a year's elaboration of the basic theory of thermonuclear explosion around a design that could not work Ulam had an extraordinary idea. He proposed a new scheme (which is still classified today), "a repetition of certain arrangements" that became the turning point for H-bomb work, and perhaps for all of us. A similar iterative scheme has presumably since been hit on in secrecy by ingenious people in four other countries.

Three distinguished mathematicians of our time have written well-known autobiographies in English: G. H. Hardy, Norbert Wiener and now Stanislaw Ulam. Ulam, the youngest, knew both of the others. Hardy's donnish disdain for the applications of mathematics and his enthusiasm for both cricket and militant atheism, like Wiener's touching expression of the life of an ex-prodigy who was childishly in need of repeated reassurance of his ability, display almost total eccentricity of style and thought. Ulam is not an eccentric but an urbane original; some of his mathematical inventions have led to profound consequences, one might say to the choice between life and death.

What Ulam tells us of his mind and his times is generally fascinating. He makes little effort to draw us into the mathematical content of his deep and varied work. He is, however, transparently honest, and he is effective in portraying his impatient, ironic and quizzical style, his ambitions, his estimates of others, his interests and his opinions with "a frankness and truthfulness which are sometimes a little strong but never really shocking."

His wordplay and comment draw now on the Latin of his excellent classical studies, now on the logical Jewish jokes of Central European cafés. When it was mentioned that Fermi would soon come to wartime Los Alamos, "immediately I intoned: 'Annuncio vobis gaudium maximum, papam habemus,'" as they say in St. Peter's when the white smoke heralds the election of a pope. Was not Fermi the infallible pope of the physicists? Later, when some mathematicians seeking Government contracts asserted the clear utility of their beloved work for national security, Ulam was reminded of the Jew who wanted to pray on Yom Kippur but tried to sneak in without paying for his seat on that crowded occasion by explaining he wanted only to deliver an urgent message. "But the guard refused, telling him: 'Ganev, Sie wollen beten' ['You thief! You really want to pray']. This, we like to think, was a nice abstract illustration of the point." A score of such tales enliven Ulam's book, as they embellished the speech of Ulam and von Neumann throughout the years. Stefan Banach, Enrico Fermi, George Gamow and above all von Neumann were friends and colleagues of Ulam's. Banach was the master of his youth as a gifted student in Lwów, one of the centers of the great blossoming of Polish mathematics between the wars. "I recall a session with Mazur and Banach at the Scottish Café which lasted seventeen hours without interruption except for meals." Ideas and proofs flowed from those conversations. Then the decision came to leave war-threatened Europe. (Of more than one of his Lwów group Ulam writes: "Murdered by the Germans.") Ulam was first a Harvard research fellow and then a faculty member at Wisconsin, a rising mathematical worker.

It is von Neumann who came closest to Ulam. They had met first in Warsaw well before the war, and they were parted only by von Neumann's death. The two men were congenial, complementary, intimate. Von Neumann displayed a not uncommon "admiration for people who had power"; indeed, Ulam thinks that in von Neumann there lay "a hidden admiration for people or organizations that could be tough and ruthless." During von Neumann's last days Ulam would read to him, in Greek, Thucydides' gripping tale of the expedition against Melos, "a story he liked especially." Von Neumann was "remarkably universal" and yet avoided "tangents from the main edifice of mathematics." He died too young of cancer, a strict Catholic near death although he had been an agnostic in life, with an enormous reputation and every honor of the mathematical world, yet "not entirely ... a mathematician's mathematician."

A mathematician such as Ulam works without external aids: no props, no equipment. Without chalk or pencil he may be at work even while walking, eating or talking. He seeks analogies between analogies. Such a person lives by this inner search and by the aid and the appraisal of a small set of peers. No wonder there is a certain detachment, a self-centered world view, an echo of fatalism. A few generous friendships of the kind that are candidly shared here with us are given to the lucky ones, but a certain coolness informs Ulam's estimate of men he found unclear, including Niels Bohr and Robert Oppenheimer. Most touching is the moment when Ulam, grievously ill with a virus inflammation of the brain, slowly recovers consciousness and speech. "One morning the surgeon asked me what 13 plus 8 were. The fact that he asked such a question embarrassed me so much that I just shook my head. Then he asked me what the square root of twenty was, and I replied: about 4.4. He kept silent, then I asked, 'Isn't it?' I remember Dr. Rainey laughing, visibly relieved, and saying 'I don't know.'"

Readers owe Ulam a debt for a book of reminiscent perceptions that have rarely been matched. A plausible conjecture suggests that we owe its coherence of form largely to an acute and sensitive Parisienne, Françoise Ulam.

EXTERNAL CONSTRUCTION BY ANIMALS, edited by Nicholas E. Collias and Elsie C. Collias. Dowden, Hutchinson and Ross, Inc. Distributed by Halsted Press, John Wiley & Sons, Inc. ($27). ALL THEIR OWN: PEOPLE AND THE PLACES THEY BUILD, by Jan Wampler.

Schenkman Publishing Company. Distributed by Halsted Press, John Wiley & Sons, Inc. ($19.95). The 21 papers or excerpts in the first of these books, by two Los Angeles behavioral ecologists, are dead serious, but the subject matter enforces a humor all its own. One Swedish ethologist watched beavers (the European species) at work, both in the forest and under controlled conditions in a big stream tank. When he came to draw from life "the beaver... on its hind legs... carrying the bundle, walking bipedally," he produced a cheerful bucktoothed fellow, arms full, who would grace any new edition of *The Wind in the Willows*.

The papers, by careful observers and experimenters from Charles Darwin and J. H. Fabre to Jane Van Lawick-Goodall and later workers, are arranged to bring out three themes: the evolutionary sequences that can be inferred from the behavior frozen in animal architecture; the economics of the inherited investments, expressed generally in terms of work, and the mechanisms by which the complex environmental manipulation is managed. Already in *The Origin of Species* Darwin reported on his use of vermilion wax as a tracer for the cell-building action of the honeybee. Here the net thrown over the species is both wide and fine-meshed, with plenty of markers, thermal measurements and simulated environments. Bees, ants, termites, caddisworms, several species of birds, mice, caterpillars, chimpanzees, spiders and the beaver are included, with the focus on their homes.

Tent caterpillars owe a great deal to the greenhouse effect of their translucent silken shelters. It is not that the wind has been divinely tempered to the harvest mouse, shorn as "with an electric clipper," but rather that the little beast has quickly built an almost complete sphere of shredded grass and the down of flower heads, deep inside which it quietly rests, thereby saving 25 percent of its fuel bill in near-zero weather. (Its fur saves even more.) Nearly all birds incubate their embryos in the egg (at a temperature of 35 to 37 degrees Celsius) by the intermittent application of a vascular hot spot on their ventral surface, the brood patch, within the context of a wide variety of nest insulations. It appears that the bird senses the egg's temperature by means of receptors in the brood patch and adjusts its sitting schedules accordingly. Bisexual incubation in shifts holds the egg temperature most nearly constant; the mode of foraging excursions during which neither parent is sitting requires an attention cycle timed by the rate of heat loss from the insulated nest. Noteworthy quantitative fits to the observations can be spun out of this kind of model with a few measured parameters.

The African weaverbirds are splendid nest builders, as the name suggests, and the two editors have studied the weaver's nest carefully. They feel that their own "weaverbird nest" built in 1960 was the first human construction of "a bird's nest of any real degree of complexity." It is a good example, to judge from their photographs. The sociable weaver is one species that has gone to live in the cold, arid Kalahari, where winter temperatures may drop at night to New England values. Instead of crowded suburbs of little short-lived one-family baskets woven of grass strips, the sociables occupy a big condominium that weighs a ton or more, accommodates 100 or more pairs of birds at a time and is handed down over decades or even a century. There is a shot of one such nest in a big acacia tree, looking rather like a Volkswagen under a scruffy tent. The measured thermal consequences are admirable: 20 degrees C. warmer inside, a legacy of perpetual food savings passed down from the hardworking early settlers. The nests appear to be limited in size by the strength of the tree, which sometimes breaks under the load. On cold nights the birds try multiple occupancy: as many as five birds may crowd into a single chamber.

The construction tricks are varied. Chimpanzees make rather cruder nests, a soft platform for rest at night and on rainy days. The technique and materials seem to a human reader to be appealingly varied and changeable. For example, in the Gombe Stream Reserve nests appeared suddenly in the tops of oil palms. They had been unknown there early in the summer of 1960, but by the end of October of 1961 they were conspicuous in many parts of the reserve. Such nests, which had been well known in other chimpanzee localities, were hard to make at first (the observer watched one young chimp give up trying and settle for another kind of tree), but they were high fashion.

Other animals can make much more complex structures than chimpanzees do, but by alien methods. Solitary bees, for example, work by rote, their inbuilt rules of sequence having rather little flexibility; theirs are open-loop programs. Fabre watched as his mason bee, after a fatal leak opened in the bottom of a pollen cell, ignored the leak and worked instead on the next courses. ("Once the provisioning begins, the cup is finished for good and all.") Termites and beavers, on the other hand, generally have programs with many closed loops, with feedback coming from the state of the work itself. The editors cite briefly, but do not excerpt, the study by Pierre Grassé on the arch-building by certain termites that yields a complex vaulted storage basement. The overall form, including the number and placement of the arches, is governed by the chance location of piles of pellets made by individual insects at work in the dark. They abandon their individual collecting at some point to increase cooperatively the piles that by chance have grown to be the largest. Two neighboring columns may be joined in an arch or may instead be abandoned for a pair that is even more favorable.

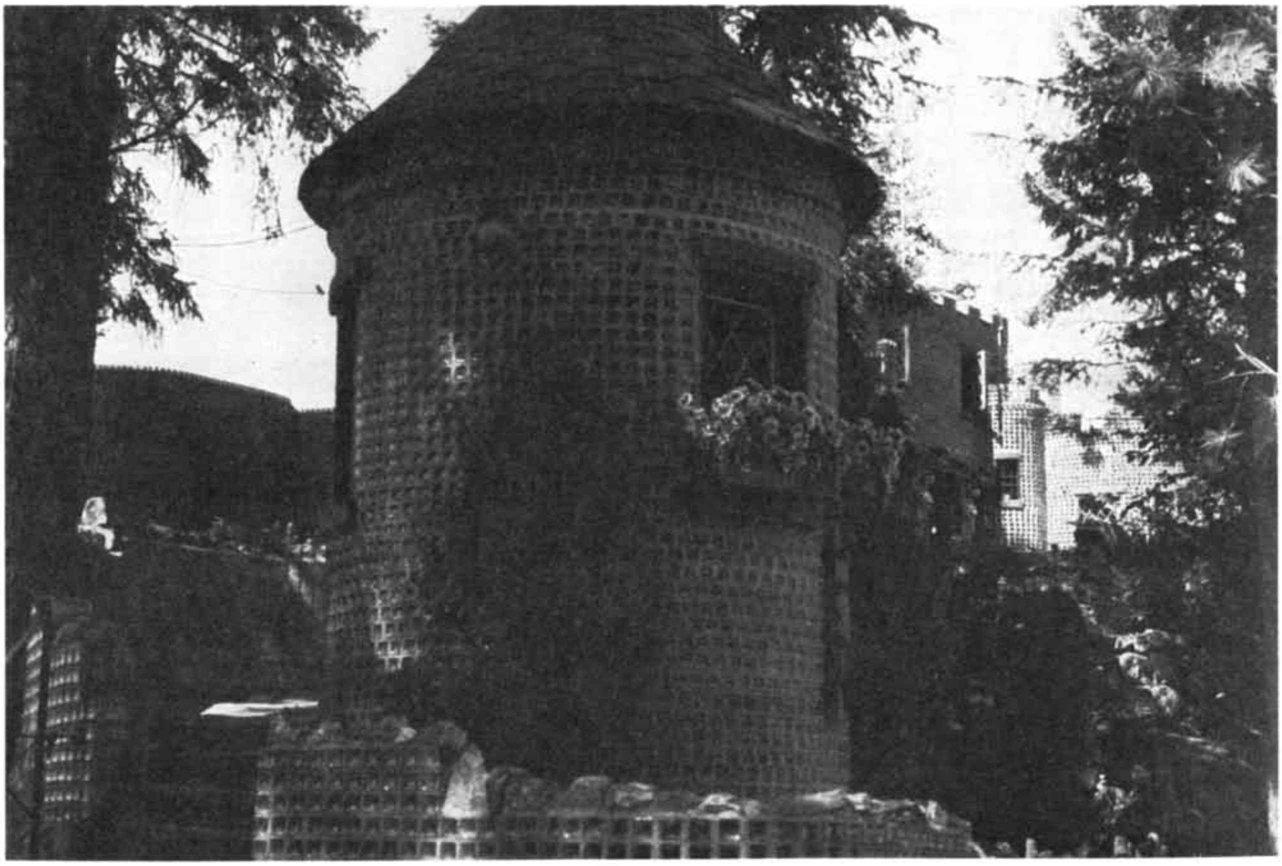
Beavers work a good deal against the sound of running water; they will build a dam on top of a loudspeaker that carries a recorded water signal (unless the signal has been filtered to leave out the one-to-two-kilohertz band). The lowan, or mallee fowl, the "native pheasant" of the dry scrublands of Victoria in Australia, places its eggs inside a big mound of fine soil, which it visits almost daily to open and ventilate in various ways. Direct thermal-flux measurements and careful controls prove that during a ma-

A beaver carries a bundle of branches, from **External Construction by Animals** jor part of the season incubation heat comes from the fermentation of a leaf mulch earlier placed under the eggs; an opening made by the birds in the morning serves during most of the season to cool the eggs. At the end of summer the mounds are left open most of the day to let solar heat enter. The overall control is excellent. We come to understand the long engineering by natural selection only through such minute particulars.

For human beings no such simple biological understanding is to be found. A gene for our architecture would require far too many alleles. An apt complement to this fine volume on animal construction is the second book, a photographic study by a professor of architecture at the Massachusetts Institute of Technology. In color and black and white he has recorded for us the works of a score of people who have built homes, shrines, gardens, decorative bridges and monuments "all their own," across the continent from British Columbia to Maine. As in the case of the towers of Watts, where Simon Rodia built beauty out of junk and his own mastery, these people have exerted remarkable effort to win the home, and sometimes the beauty, they sought. Their materials, scale and ambitions vary. A mansion on the shores of Lake Kootenay in British Columbia has walls, towers and bridges made of identical empty one-quart embalming-fluid bottles—about half a million of them—laid up in mortar like bricks. There is a man in a small house in Eureka, Calif., who lives quite hidden behind a garden filled with trees, large flowers, fences and animals—all carved from orange-crate ends and then painted gaily and wittily. "I no make things now for four or five years. No more room, no more boxes. Now all the boxes they come in paper, no wood." Perhaps the most beautiful creation, if not the most spacious or architectural, is Fred Burns's little cottage on Belfast Harbor in Maine. Made of driftwood and covered with leftover paint, it is a striking work of ordered polychrome texture that resembles some striped canvases of the school of New York. It is the public offering of a unique, solitary and loving artist.

REMOTE SENSING OF ENVIRONMENT, Joseph Lintz, Jr., and David S. Simonett, editors. Addison-Wesley Publishing Company, Inc. ($27.50). GRAND DESIGN: THE EARTH FROM ABOVE, by Georg Gerster. Paddington Press Ltd., New York and London ($50). Eyes we have had for a long time, and the use of instruments for apprehending what is out there is not anything new to science or to its applications. *Remote Sensing of Environment,* with 20 expert contributors, surveys under its somewhat ill-fitting rubric an important, vigorous and still-forming young discipline: the use of electromagnetic radiation to look down through the atmosphere at the surface of this earth from above, whether from a cliff, an airplane or a spacecraft. Medical and production-line tasks are excluded, and (although they are more germane) so are all military activities, even though it is the development of the remarkable military reconnaissance programs that has indirectly paced civilian technology in the postwar years.

There is plenty to talk about in this heavy volume with 48 pages of references. The work is in four fairly distinct parts: the foundations of radiation physics and the effects of the atmosphere; the bases of sensor instrumentation; calibration and handling of the data flood, and summaries of results and promises in a number of fields of current application. Eight pages of color pictures display the tricks of this art, and there are many drawings and tables. Integrals and even the Navier-Stokes equation are to be found, but they are chiefly for the purpose of careful definition, the basis of prose accounts that are occasionally rather formal. In general the mathematical level is modest, below that of the



A mansion built of empty embalming-fluid bottles, from **All Their Own: People and the Places They Build** engineer or physical scientist; the authors are concerned that the users of the work include planners and managers of fisheries, forests, mines and highways.

The chief theme is image: the two-dimensional plot of the geography of the surface. Sometimes the image is made by ambient light and sometimes the flying imager carries its own flashbulb. Black-and-white values are the starting point, but the discipline is enriched by color, a major topic. The "ambient light" includes the visible and the near infrared, fed by sunshine; it does not lack ultraviolet, which can discern fluorescent markers laid out below, or the subtle thermal infrared at 10 microns, whatever the atmosphere will pass. Color is stretched to include centimeter radio waves, which are intrinsic emissions of marshes or even snowbanks, and the lowest radio frequencies, valued for their ability to probe into the earth for ore bodies. "Ambient light" can include even the strong, very-low-frequency emissions of government time-signal and navigational stations. Such 20-kilocycle waves from Australia induce currents in the rocks of Fiji, 3,600 miles away; the currents are weak but are still strong enough to make possible detailed mapping of the rugged surface for a complex of conductive properties related to mineral deposits. Even lightning storms can be exploited in the same way, and other schemes exploit natural gamma radioactivity or the luminescence of chlorophyll or of minerals.

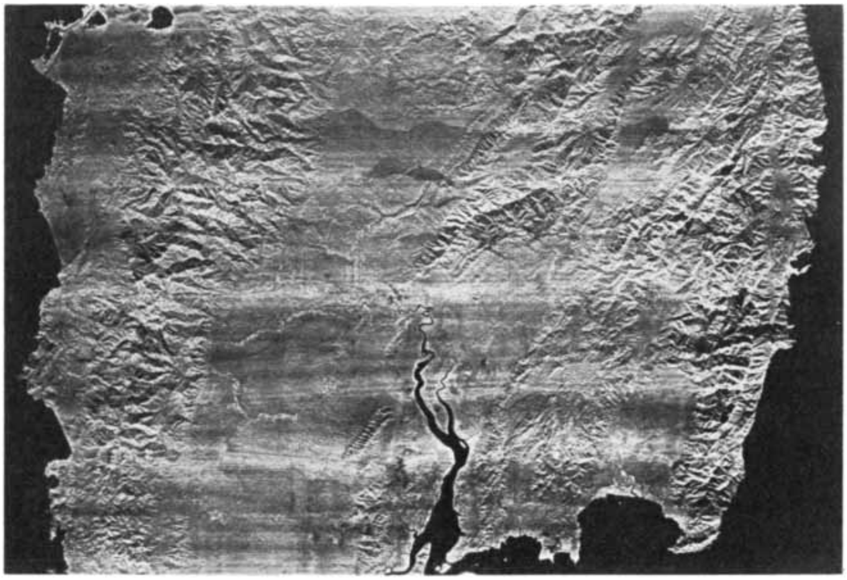
Most people have now seen the remarkable relief mapped by side-looking airborne radar. A directed radar pulse in the centimeter band marks out a spot to each side of the plane as it flies along. The spot may be 100 feet in diameter on the ground; the echo delay is easy to record in flight, so that the system produces an image much as the scanning electron microscope does, with a great "depth of focus" and with gray values that represent the microwave texture of the surface being scanned. By this means it has been possible to map a piece of the Isthmus of Panama that had resisted all aerial cameras because it was always covered by clouds. In 1971 the government of Brazil organized such radar mapping of the green Brazilian north; an area half as big as the U.S. was mapped in a number of different modes in a very short time. Here is a clear photograph of Boston Harbor made at three in the morning; darkness is not much of a barrier for the deep infrared. A thermal peek into the crater of Kilauea shows the arrangements in Pele's kitchen; another page exhibits the multiband spectral patterns that can distinguish among a dozen crops, field by field.

The art is a fledgling still. Its best-known civil exemplar is LANDSAT, once called ERTS. That nimble satellite flies over you in the morning 20 times a year, its imagers busy. The world is now well mapped by LANDSAT, at a resolution of better than 100 meters. A map of the U.S. at that detail occupies only a few ounces of film; telemetry can bring it down to earth in pulsed form in an hour. (Narrow down the resolution to a couple of feet and you must reckon on a ton of film, a half-year of data pulses.) LANDSAT's best-known product is the result of scanning point by point in four bands, with photographs made available cheaply to the public through the National Aeronautics and Space Administration and the U.S. Geological Survey. The color is not that of our vision but of a flexible code that represents the seen and unseen reflectivities by various groupings into mapping colors. By 1980 a proposed LANDSAT-D satellite may map in six or even seven channels that are chosen to indicate the vigor and nature of growing green plants, following a lead given by aerial studies of corn blight. LANDSAT is an experimental success worldwide, and several other countries are considering launching such satellites soon.

How to handle a ton of film? Obviously our eye-mind system will need help. Much effort has been put into that assistance. On the one hand, nifty schemes are available to superpose images from many channels in a variety of colors and contrasts and to record what is good. Other work has been done on numerical codes, with sophisticated statistical algorithms teaching the computer to signal interesting clusters of points in color space, a form of pattern recognition that is not yet easy but will in the end be indispensable. The keys to such schemes are a clear purpose and careful calibration on known spots presented to the high lenses in exactly representative ways. Such calibration, known by the philosophical name of "ground truth," is a requisite; the obvious competitor, an image library for general comparison, has not yet worked promisingly. Sea and ice, cloud and land, hot desert and cool marsh, good crops and poor, texture and mineralogy and roughness, houses and engines, streetlights and much more lie below the radiometers, cameras and radars in satellite, helicopter and Lear jet. From far away our blue marble is enigmatic and bland, perhaps four-tenths cloud, but from 1,000 kilometers on down to the rooftops and hedgerows more and more of all we do and all we have will stand on the record.

So much for science and engineering, civil and military. The aerial photograph can also be a work of art. In *Grand Design: The Earth from Above* the art is practiced at low altitude from light, high-wing monoplanes chartered by the artist in almost 60 countries, the door removed, the brave photographer leaning out with his hand-held camera motorized for split-second action. The sharp lenses and fine-grained films of our time make equipment larger than the 35-millimeter camera unnecessary even for these big full-page reproductions of 200 sites on this our earth. They are in color, here fully natural, and in black and white. They present, with revealing notes of interpretation and history, six categories of views, unified by the 1,000-foot scale characteristic of this artist.

For each category we sample a few views: for the natural background, the San Andreas fault, quite bare, and the pattern of gnu trails in the Serengeti; for the roofs of humankind, Danish campers in their circles and the round huts of a Songhai village on the Niger; for in-



Side-looking radar mosaic of Panama, from **Remote Sensing of Environment. (South is at top.)**

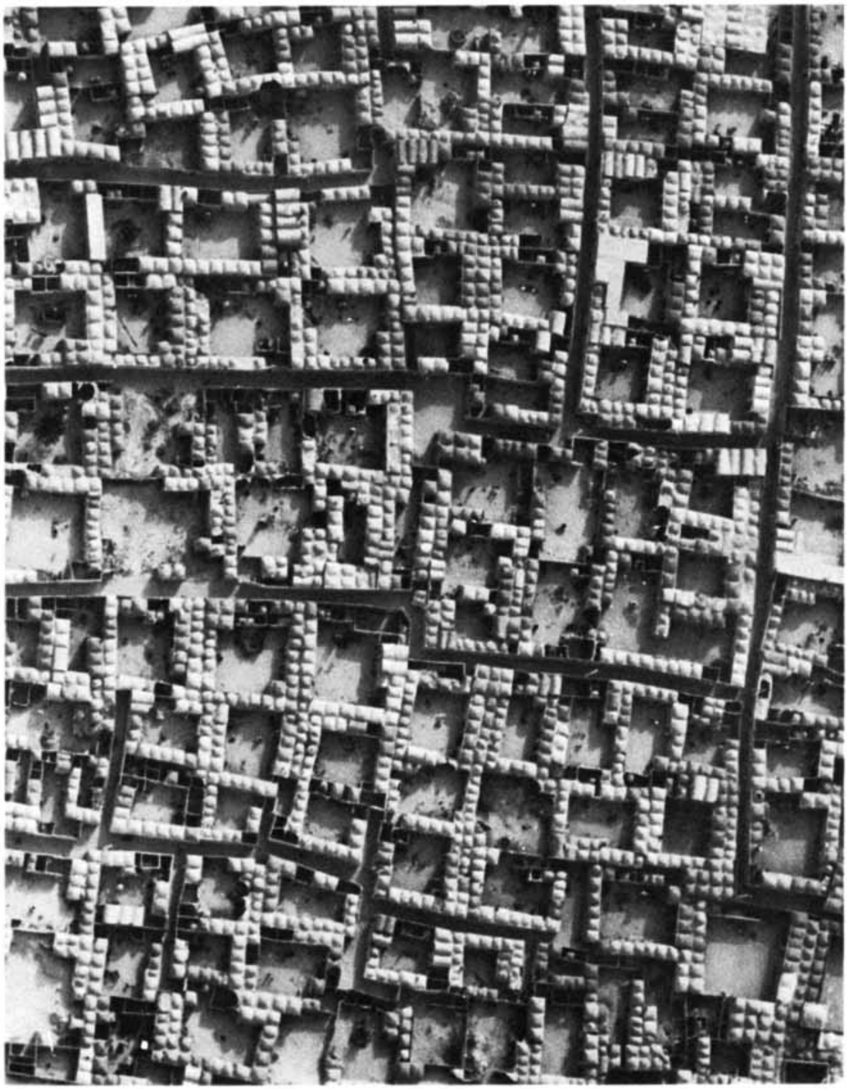
dustry, a road in red laterite slashed across the green Mato Grosso and a "large-scale Paul Klee"; salt evaporating ponds, a most unexpected category, offer their algal palette from San Francisco to Ethiopia; the farmer as artist has given us a California poppy field, a terraced Kyushu landscape of precise beauty, mixing rice fields and tangerine orchards, and irrigated circles of alfalfa in Nebraska. We see timeless Jericho and Jerusalem; artists new and old have deliberately prepared the Spanish Steps and Robert Smithson's encrusted spiral jetty in the Great Salt Lake. Finally, between art and worship, we steal a glimpse at what was limned for the gods: the White Horse of Uffington engraved across green downs, and the Great Serpent Mound of Ohio, curling over his hills.

A decade ago Gerster contributed some of the finest images to a smaller but equally wonderful collection (*The World from Above*). The deep protective cups among desert dunes that shelter the date palms in the Souf Oasis in Algeria were shown, and they are here again in different shots. (We miss in the new book the data that in the earlier volume gave the altitude or scale for each photograph.) When Gerster's six-year-old said her prayers at night, she asked: "In the plane give him many beautiful views and don't let the hyenas eat him." All of this was granted. Those wondrous pyramids of Kano stretch below us, 80 or 100 of them, crystalline and lofty, all built anew each crop season by the labor of men working without cranes, hoists, wheels or ramps, each pyramid a pile of 10,000 heavy sacks of peanuts!

WHEREBY WE THRIVE: A HISTORY OF AMERICAN FARMING, 1607–1972, by John T. Schlebecker. The Iowa State University Press ($12.95). THE AMERICAN FARM: A PHOTOGRAPHIC HISTORY, by Maisie Conrat and Richard Conrat. Houghton Mifflin Company ($17.50). "History celebrates the battlefields whereon we meet our death, but scorns to speak of the plowed fields whereby we thrive. It knows the names of the kings' bastards but cannot tell of the origin of wheat. This is the way of human folly." Schlebecker, a professional historian and curator of the collection of agricultural implements at the Smithsonian Institution, has given us some escape from those strictures of J. H. Fabre. His modest and readable narrative offers a brief history of American farming, at once social, economic and technological. Its structure is transparent: he breaks the long span into periods divided by the four major wars. Within each period he treats land, markets and technology, merging other issues when appropriate. The work does not seek to break fresh ground; it is a secondary history, supported not by footnotes but by a good bibliography. There are many small illustrations (period engravings and photographs), mostly showing implements and methods of the past. The complex story cannot be summarized here, but a few points repay the telling.

The Indians farmed first, ably with hoe and stick. Their staple was maize, and the new European farmers emulated what they saw. To the South the Africans came, to apply their intensive garden methods. Plows and heavy horse tillage, like the staple wheat itself, came rather slowly; bread grains meant more work and less yield, but they could be sold abroad. Commercial farming began in Virginia, first with tobacco, a Venezuelan variety worked by indentured Englishmen. Slavery, the "peculiar institution," arrived in about 1675; the Africans brought sorghum and probably the first rice. King Cotton passed tobacco in importance by 1803. America was a major source of industrial raw materials for England and Europe. The world opened to cheap clothing made of American cotton that was spun and woven in English mills.

In the 1840's Joseph Dart of Buffalo began to use the chain-bucket elevator, instead of the manhandled sack of long tradition, to transfer grain in bulk on canal boats. He added steam power to the process, which had been invented in 1785 by Oliver Evans. Bulk shipment soon made the world one market for grain. Minnesota and Alberta, the remotest plains, benefited the most from improvements in transport and storage, and the wheat trade became theirs; the farms of Pennsylvania and Sussex could not easily compete. Soon the sulky gang plow, with the plowman riding and two plow bottoms at work, brought "the rapid conquest of the prairie." There was plenty of pull in the three-horse team. In time the ripe fields saw the advent of the mechanical reaper and then of the harvester, the thresher and finally the combine. Steam threshed the wheat, 80 per-



An oasis town in the Algerian Sahara, from **Grand Design: The Earth from Above**

A child cranberry picker in 1910, from **The American Farm: A Photographic History**

cent of it by 1880. The combine took over after World War I, gasoline-powered by that time. The word "tractor" was first given by Charles Hart and Charles Parr of Iowa to their implement-hauling machine in 1906. (A 1903 Hart-Parr in the Smithsonian still runs.)

The U.S. farm population reached a broad plateau in absolute numbers in about 1910 and stayed level until the eve of World War II. Since then it has fallen by a third each decade. Now the farm is industrialized, cartelized and remarkably productive as measured by hours of labor or by acres of land. Its inputs are hard work, capital, education, high technology from anhydrous ammonia to maize genetics, and plenty of fuel B.t.u.'s. The driven-spindle cotton picker had become common by the 1950's, and so the cotton farmer sent the black sharecropper and his family off to the cities north and south with no savings and no city skills. Every page of this cool narrative holds between the lines both inequity and promise.

For the second book two Californians, photographer and designer, have assembled the work of 80 photographers from more than 100 picture archives. The foot-wide pages bear their selections, a couple of hundred prints, filled with the look of the land and its people, made between 1860 and 1973. A man is sowing grain broadcast in Maine in 1885, his hand swinging wide as he strides his field as farmers have done for 10 millenniums. A slave family on a South Carolina plantation in 1862, three generations in front of their cabin, look straight through T. H. O'Sullivan's lens at you, grave, intent, direct. A small boy builds a structure of corncobs as his grandfather shells corn in a New England kitchen in 1900. Here are the "Sooners," sod shanties, bales of cotton on the levee, teams of oxen, Chinese in conical hats tending California vines, even covered wagons ready to ford a Wyoming stream on the Oregon Trail as late as 1875. Here is a drought-dusty windrow on an abandoned Oklahoma farm in 1936, and a thin-armed farm woman, taut, worn and enduring, in Dorothea Lange's moving photograph. The silent pages seem to echo with old songs we all know, both the defiant and the sad. Toward the end the entire scale changes. Now we see fewer people; here are wide rolling fields, the heavy combines busy, and airplanes above, crop-dusting or ferrying repair parts for the costly machines. The Imperial Valley spreads out table-flat and field-tiled; the crops are in meticulous array but there are no farmhouses. An 80-year-old farmer is cited for the last word: "These big farmers, now, they retched out and got all the land. The little guy don't get by no more."

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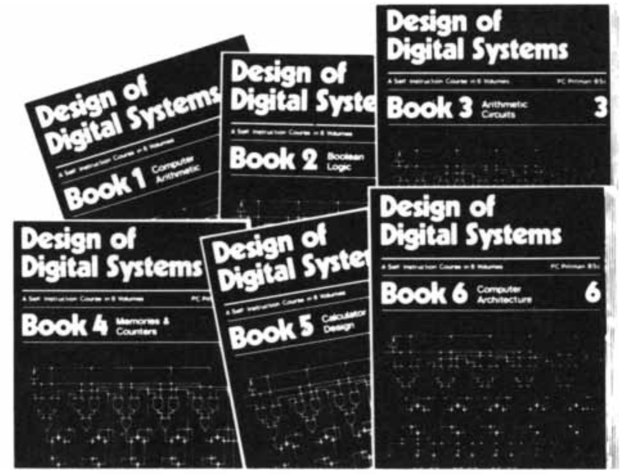

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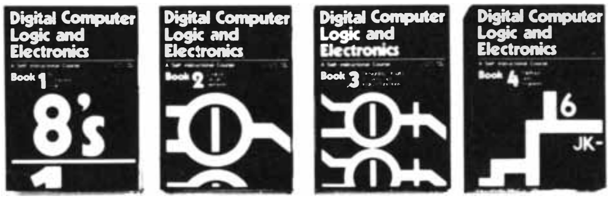

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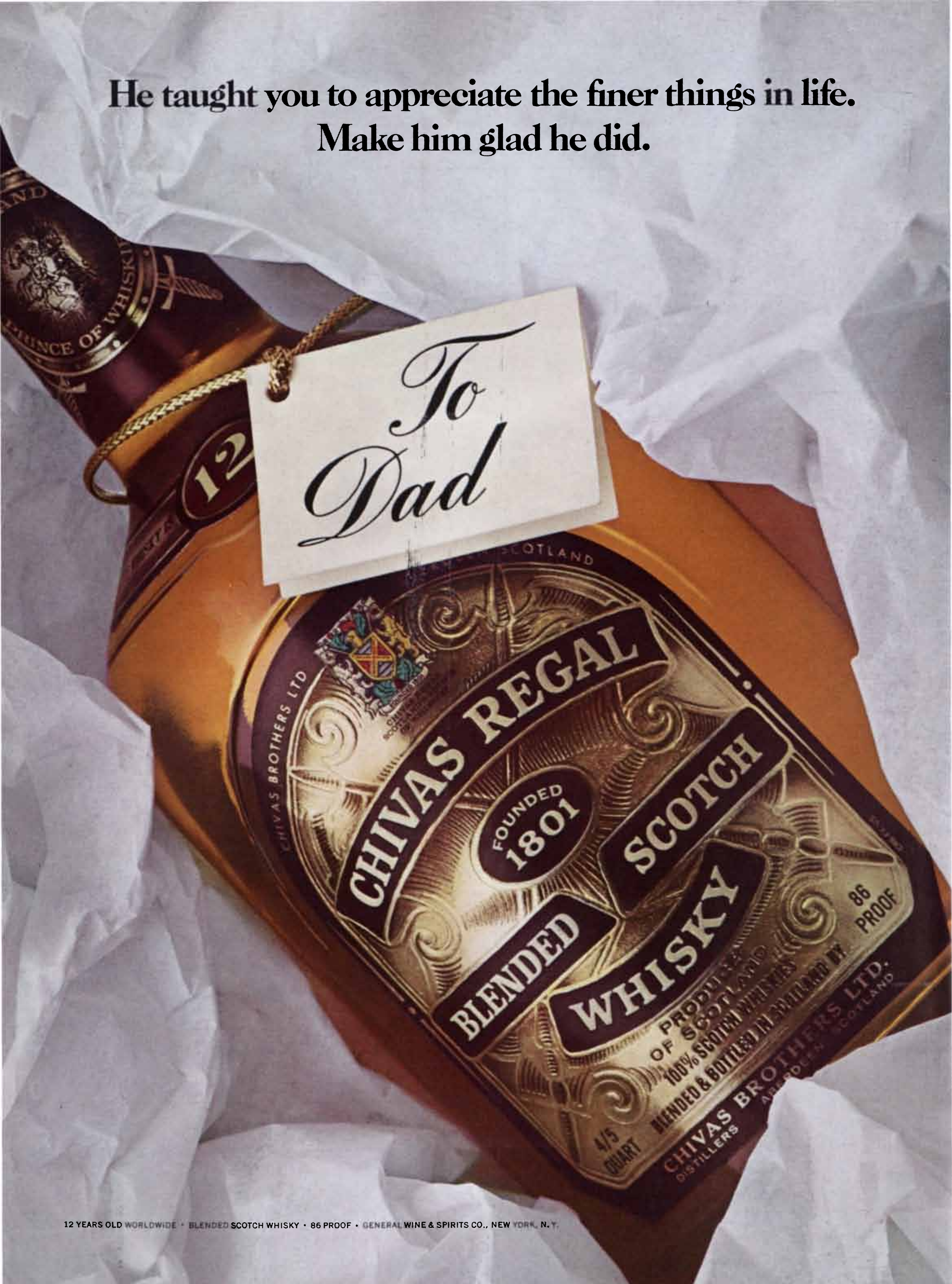
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