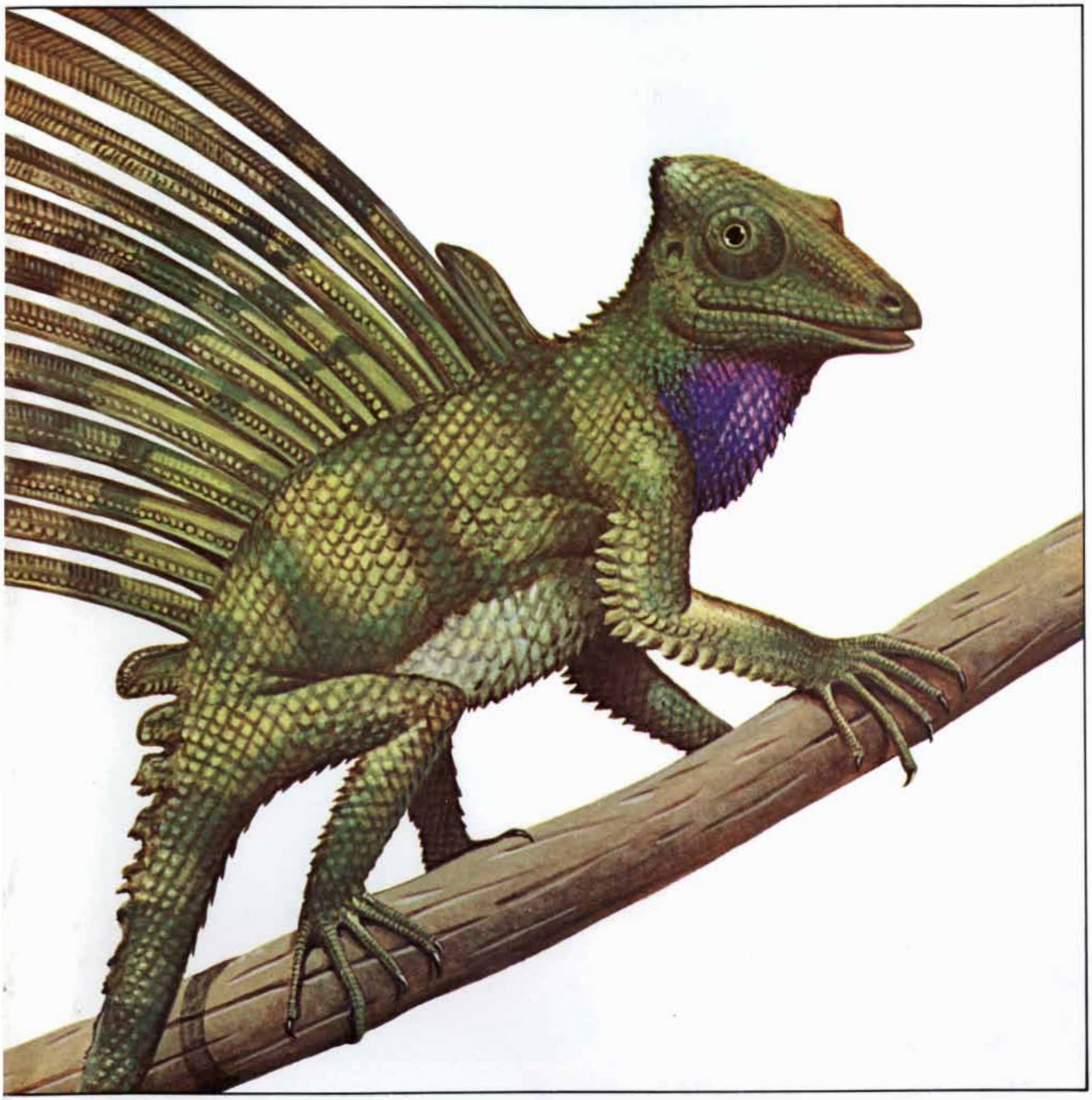
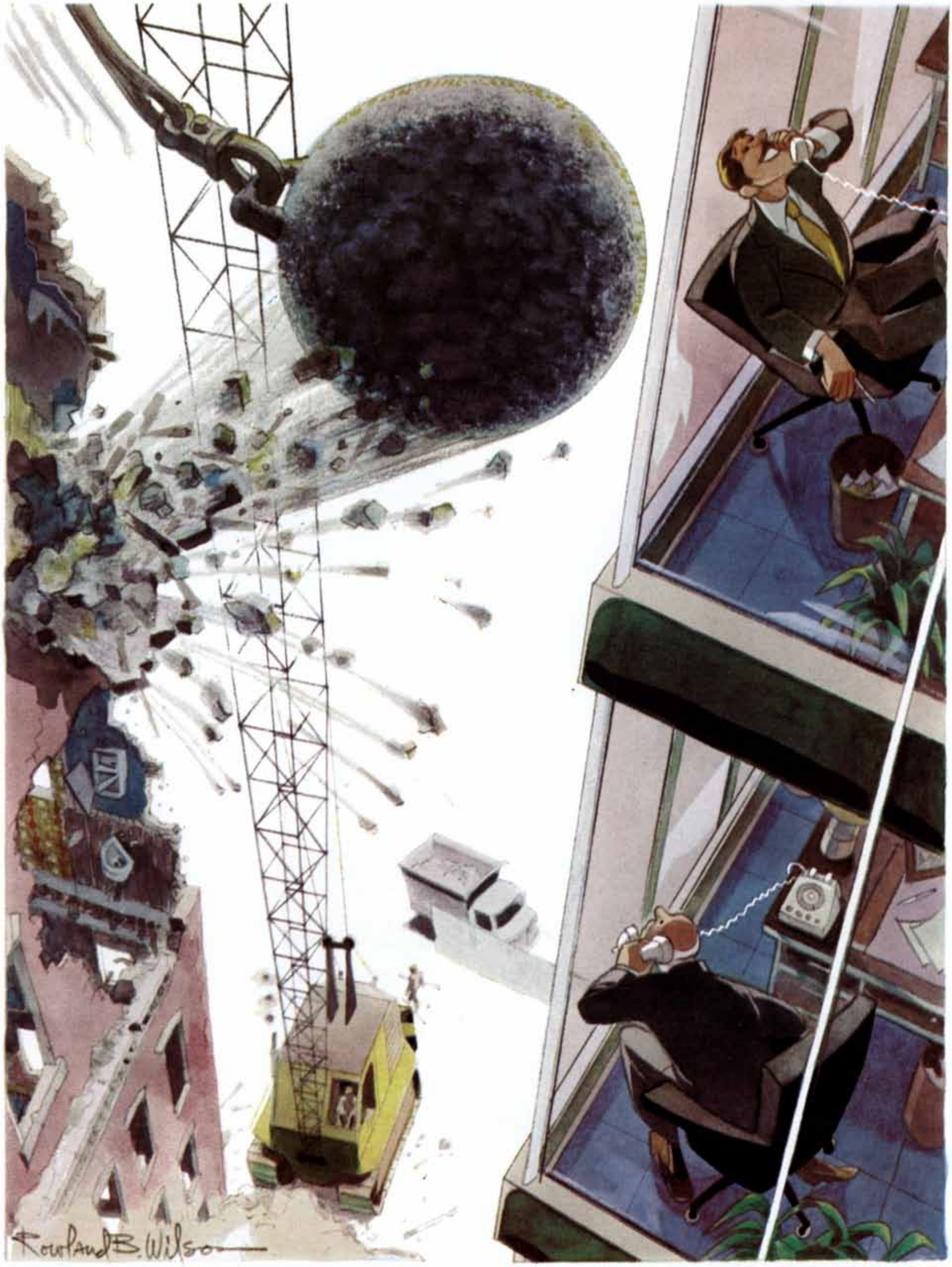
# SCIENTIFIC AMERICAN



DINOSAUR RENAISSANCE

$1.25

April 1975

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Established 1845 **SCIENTIFIC AMERICAN** April 1975 Volume 232 Number 4

ARTICLES



DEPARTMENTS





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## THE COVER

The painting on the cover depicts *Longisquama,* a tiny (less than six inches long) creature that lived in the Triassic period some 225 million years ago. It was a thecodont, a member of a group that was descended from early reptiles and included the ancestors of the dinosaurs. Unlike typical reptiles, most thecodonts were "warm-blooded," like mammals and birds. And so too, it appears, were the dinosaurs (see "Dinosaur Renaissance," by Robert T. Bakker, page 58). *Longisquama* had plumelike devices on its back and a covering of insulating scales; such scales are a stage in the evolution of feathers. *Longisquama* is part of the evidence that dinosaurs were not reptiles but a novel "warm-blooded" group, and that they are not really extinct after all—that the birds are a living group of dinosaurs.

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# SCIENCE/SCOPE

Now undergoing sea trials aboard a U.S. Navy destroyer escort is a fully automatic air defense system built by Hughes. Designated the Improved Point Defense/Target Acquisition System, it is the first to integrate infrared sensors with conventional radar and correlate the returns. IPD/TAS will give single ships the reaction speed they need to defend against low-flying aircraft that "pop up" over the horizon.

A more accurate inventory of the world's food crops will be a major assignment for Landsat II, the new earth resources technology satellite launched by NASA in January. Photographs by the satellite's Hughes-developed Multispectral Scanner (MSS) will enable agricultural scientists to measure acreages and predict yields, and to determine the long-term relationship between yields and climatic patterns. The new technique was called "a promising and potentially vital contribution to rational planning of global production" at the recent World Food Conference in Rome.

Landsat II's continuous-strip photos will also be used to locate air and water pollution, map strip-mine and forest-fire devastation, locate underground water supplies, update maps and navigation charts, locate geologic formations indicating the presence of petroleum or minerals, monitor urban developments, and evaluate fishery resources. Data from the MSS photos can also be fed directly into computers.

A way of conserving U.S. R&D dollars by adapting an already designed European air defense system was made possible recently when the Hughes-Boeing proposal to build a short-range, all-weather air defense system was selected over three competitive proposals. The SHORADS system is equally suited for installation on tracked or wheeled vehicles or fixed installations to defend against low-flying aircraft.

Hughes needs Training Engineers to prepare civilian and military personnel to efficiently operate and maintain the AIM-54A Phoenix Missile System. Training Engineers conduct classes at Hughes' California sites and domestic and foreign locations. BSEE or Physics degree and U.S. citizenship required. Please send your resume to: D.J. Wingate, Hughes Aircraft Co., Support Systems Division, P.O. Box 90515, Los Angeles, CA 90009. An equal opportunity M/F employer.

Industrial waste heat can be put to work by the new Hughes Heatbank™ heat recovery unit, a compact, self-contained, passive heat exchanger with no moving parts or external power requirement. It is designed to heat an incoming airstream, using the otherwise wasted thermal energy from a warm exhaust airstream. Applications include industrial furnaces, paint-drying and processing ovens, food drying, petroleum refining, and glass, plastic, and papermaking processing. For information, write: Hughes Thermal Products, 3100 W. Lomita Blvd., Torrance, CA 90509.

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# LETTERS

Sirs:

I enjoyed Martin Gardner's essay on "nothing" [Scientific American, February]. John Horton Conway's rule and Gardner's analysis of "nothing" are, like all human activity, expressions of the nervous system, the study of which helps in understanding the origins and evolution of "nothing."

The brain is marvelously tuned to detect change as well as constancies in the environment. Sharp change between constancies is a perceptually or intellectually recognizable boundary. "Nothing" is "knowable" with clarity only if it is well demarcated from the "non-nothing." Even if it is vaguely bounded, nothingness cannot be treated as an absolute. This is an example of the illogicality of absolutes, because "nothing" cannot be in awareness except as it is related to (contrasted with) non-nothing.

One can observe in the brains of perceiving animals, even animals as primitive as the frog, special neurons responding specifically to spatial boundaries and to temporal boundaries. In the latter, for instance, neurons called "off" neurons, go into action when "something," say light, becomes "nothing" (darkness). "Nothing" is therefore positively signaled and is thereby endowed with existence. The late Polish neuropsychologist Jerzy Konorski pointed out the possibility that closing the eyes may activate off neurons, giving rise to "seeing" darkness and recognizing it as being different from not seeing at all.

I and others have used temporal nothingness as a food signal for cats by simply imposing 10 seconds of silence in an otherwise continuously clicking environment. Their brains show the learning of the significance of this silence in ways very similar to those for the inverse: 10 seconds of clicking presented on a continuous background of silence. "Nothing" and "something" can be treated in the same way as psychologists deal with other forms of figure-ground or stimulus-context reversal.

The nothingness of which we become aware by specific brain signals can be known only by discriminating it from other brain signals that reveal the boundaries and constancies of existing objects. This requires an act of attention. There is another form of "nothing" that is based on an attentional shift from one sense modality to another (as in the example of listening to music) or to a failure of the attentional mechanism. In certain forms of strokes the person "forgets" one part of his body and acts as if it simply does not exist, for example a man who shaves only one half of his face.

Animate systems obtain and conserve life-supporting energy by evolving mechanisms to offset or counter perturbations in their energy supply. Detecting absences ("nothings") in the energy domain had to be acquired early or survival could not have gone beyond the stage of actually living in the energy supply (protozoa in nutritious pools) rather than near it (animals that can leave the water and return).

If this pragmatic view of the biopsychological origins of "nothing" and "absence" is insufficient for trivializing the Leibnizian question ("Why should something exist rather than nothing?"), I would argue that the philosopher faces the necessity of showing that the statement "Nothing [in the absolute sense] exists" is not a self-contradiction.

Vernon Rowland, M.D.

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Case Western Reserve University
Cleveland

**Scientific American,** April, 1975; Vol. 232, No. 4. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and secretary; George S. Conn, treasurer; Arlene Wright, assistant treasurer.

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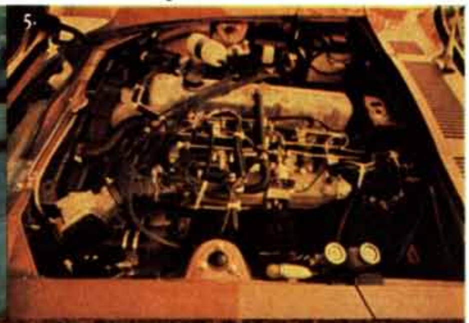



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by Allen Mac Kenzie

Perhaps the most elusive quality of any Scotch whisky is the ability to retain freshness as it dilutes with ice. While no Scotch can be totally "ice-proof," it can be demonstrated that a 90-Proof Scotch will sustain its freshness substantially longer than Scotches bottled at 80, 86, or 86.8 Proof.

Our motive in presenting this demonstration is quite simple: our brand of Scotch Whisky, *Famous Grouse,* is the only Scotch now available in this country at 90 Proof. If you are an "on-the-rocks" Scotch drinker, we presume you are a seeker of long-lasting freshness and will take the time to consider our argument.

### A Comparison of Proofs

To demonstrate the merits of a slightly higher proof, we performed a simple experiment: 50 millilitres of Scotch (about 1.7 ounces) was chilled with 100 cc of ice. The ensuing dilutions at 80, 86.8 and 90 Proof are charted in the graph at left.

You'll notice that after 15 minutes on the rocks, the proof of *Famous Grouse* is diluted to a level which occurs after 12½ minutes when the Scotch is 86.8 Proof, and after 9 minutes when it is 80 Proof. In essence, the *Famous Grouse* brand has remained about 2½ minutes fresher than 86.8-Proof Scotch (Interval A on graph), 6 minutes fresher than 80-Proof Scotch (Interval B). If you "nurse" a drink beyond 15 minutes, the advantages of 90-Proof Scotch are even more pronounced.

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Proof, of course, is not the only influence on the flavor of a blended Scotch. The proportion of malt to grain whiskies, origins of the malts, aging methods—these are also important factors determining the relative richness of Scotch flavor.

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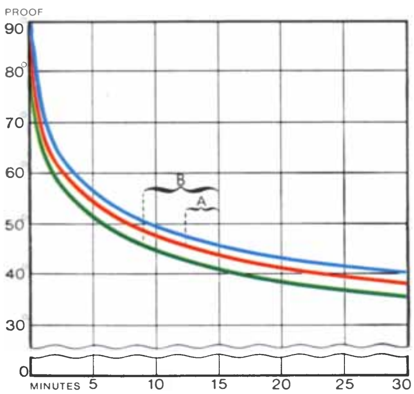
Graphs and calculations can carry you only so far in the search for a perfect Scotch on the rocks. The ultimate experiment requires that you pour a portion of *Famous Grouse* over ice and submit the decision to your palate. In the words of the great bard, Robert Burns:

*"From scenes like these,*
*Old Scotland's grandeur springs."*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# 50 AND 100 YEARS AGO

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APRIL, 1925: "The cities that border on the Great Lakes are greatly exercised over the lowering of the levels of these inland seas. With the growth in the size and draft of ships, the question of sufficient depth in canals and harbors has become acute. The decrease in depth has been brought about by the creation of various artificial discharges from the lakes. The most important of these is that through the Chicago River to the Des Plaines–Illinois rivers and thence into the Mississippi. Formerly the sewage of Chicago flowed into the Chicago River and emptied into Lake Michigan, from which the city draws its water supply. In order to divert this sewage from the lake the flow of the Chicago River was reversed, and by means of widening, dredging and a connecting canal, known as the Chicago Drainage Canal, the sewage was diverted into the Mississippi."

"We are on the verge of developments that have for their object the elimination of batteries from radio receivers. It is an almost immediate necessity that commercial lighting current be made to serve as a source of current for vacuum tubes. There is considerably more to this problem than the mere reduction of the voltage to low potentials, and there is still more than the conversion of alternating current into direct current. Where the real obstacle comes in is in the elimination of troublesome hum. After several years of experimentation radio engineers have evolved methods of harnessing lighting current to the vacuum tube. The methods call for vacuum-tube rectifiers, the output of which is smoothed out by high-value inductances and capacitances."

"Twenty-one years ago the chestnut blight, or bark disease, was first noticed in a tree in the New York Zoological Park. From this center the blight spread, and it is now close to the western limit of the tree's natural range. By repeated grafting and hybridization it is now hoped that trees having an immunity to the blight will be developed. The common American chestnut and the European chestnut are both very susceptible to the destroying pestilence, but the Chinese chestnut and the Japanese chestnut are resistant to it. Specimens that appear to be immune from attack are cross-bred, and from their offspring individuals showing increased disease resistance are selected. In this manner varieties that are comparatively free from the disease are developed."

"A striking feature of the recent solar eclipse was the prominence of the shadow bands. They first appeared some five minutes before totality as narrow, pale, flickering strips of shade, two or three inches wide and six or eight inches apart. As the light faded they became more and more prominent. During the last minute of sunlight everything was covered with a mad maze of narrow, dark, flickering, squirming bands, so conspicuous that they must have attracted instant attention from anyone who looked at the ground. There can be little doubt that these shadow bands are the actual shadows of streaks of irregular density in the air. What causes the shadows is the unequal refraction of light by streaks of warmer and cooler air. Why do we not see shadow bands every day? If the sun were a mere star-like point, there is no doubt that we would see them often. Actually the sun shows a large disk, and shadows are far from sharp except close to the objects that cast them. Only when the disappearing sun is reduced to a narrow crescent do the bands appear."

"A Chicago man has invested $200,000 in a laundry. It is not an ordinary laundry but one for motor cars. The automobile is first pulled through a 'shower' on an endless belt, then rubbed down by hand with chamois cloths."

SCIENTIFIC AMERICAN

APRIL, 1875: "According to the theoretical view proposed by Thomas Young and more fully developed by Helmholtz, the eye perceives but three colors or wavelengths, and all the other colors and shades known to us arise from the compound of the primary ones in the eye. The light waves are received by a layer of the retina, called the rods and cones, where experiments have led investigators to believe that the sensation of sight is located. The layer is named for the shapes assumed by the optic nerve substance there, which is supposed to be tuned to the reception of color vibrations. Professor Max Schultze says: 'The rods and cones must be considered the terminal organs of the optic nerve; in them must take place the translation of the action of light into nervous action, which process ultimately lies at the foundation of the act of vision.' Although we can reason that the conversion of light into sight must take place here, we do not seem to have approached a knowledge of how it is accomplished."

"A wire-rope traction railway, the invention of Mr. A. S. Hallidie, has been adopted by the Clay Street Hill Railroad Company, in the city of San Francisco, Calif. The system consists of an endless wire rope placed in a tube below the surface of the ground, between the tracks of the railroad. It is kept in position by means of sheaves, upon and beneath which the rope is kept in constant motion during the hours the cars are running. The power is transmitted from a stationary engine to the rope by means of grip pulleys, and from the rope to the cars on the street by means of a gripping attachment on the car, which passes through a narrow slot in the upper side of the tube. The route of the railroad in San Francisco is exceedingly irregular. The average grade is 580 feet to the mile and the steepest 850 feet to the mile. The length of the steel rope is 6,800 feet, the circumference three inches. The rope runs at the rate of about four miles per hour and the ascent is made, including stoppages, in about 11 minutes. The motive power is supplied by a steam engine of 30 horsepower."

"An annual report of the Massachusetts Bureau of Statistics contains some interesting facts touching on the wages and manner of living of working people in that state. The statistics were gathered by personal visits with 397 families. Of the 142 families in which the father was the only worker, the average yearly income was $723.82; of the 255 families in which the wives or children assisted, the average income was $784.38. From the tabulated returns the bureau has concluded that in the majority of cases working men do not support their families by their individual earnings alone but rely, or are forced to depend, upon their wives or children for from one-fourth to one-third of the family earnings. Children under 15 years of age supply, by their labor, from one-eighth to one-sixth of the total family earnings."

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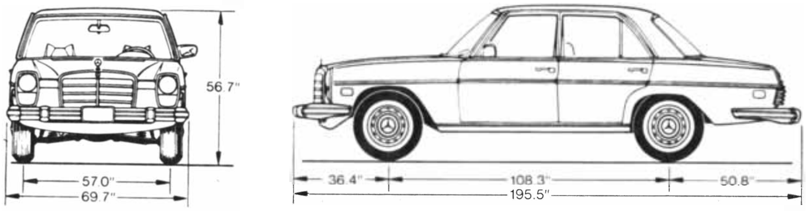


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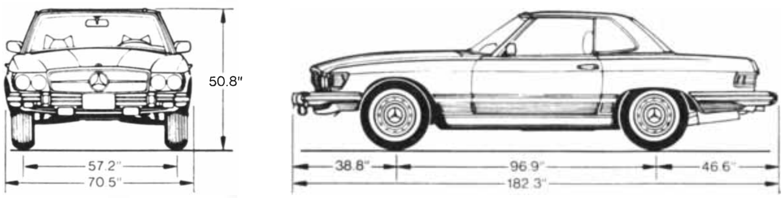


Mercedes-Benz luxury sports cars. *Above, 2-seat 450SL. The 4-place 450SLC, 14 inches longer.*

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# THE AUTHORS

WILLIAM EPSTEIN ("The Proliferation of Nuclear Weapons") is a Special Fellow at the United Nations Institute for Training and Research (UNITAR), where his work is supported by the Rockefeller Foundation and the Beulah Edge Trust Fund. (The latter fund is administered by the UN Secretary-General.) Epstein recently retired from his post as director of the Disarmament Division of the UN Secretariat, where, he writes, he had been "continuously involved in the work of arms control and disarmament in an official capacity since 1950." A Canadian, he was educated at the University of Alberta, where he received his B.A. and LL.B. degrees, and at the London School of Economics, where he did postgraduate work in international affairs. After serving in the Canadian army in World War II he joined the staff of the UN Preparatory Commission in London in 1945. In the early years of the UN he worked as a senior political officer in Palestine and as head of the Middle East Section of the Secretariat. Later he represented the Secretary-General at the meetings of the Conference of the Committee on Disarmament in Geneva and at numerous other conferences on the problems of the arms race, including nuclear proliferation. On his retirement last year Epstein was appointed visiting professor at the University of Victoria in British Columbia. He continues to serve as a consultant on disarmament to the Secretary-General.

BELA JULESZ ("Experiments in the Visual Perception of Texture") is head of the Sensory and Perceptual Processes Department at Bell Laboratories. A native of Hungary, he was graduated from the Technical University of Budapest and the Hungarian Academy of Sciences. In 1956 he joined Bell Laboratories, where he was first engaged in developing digital methods of encoding pictorial information. Since 1959 he has devoted full time to research on visual perception.

ANTHONY CERAMI and CHARLES M. PETERSON ("Cyanate and Sickle-Cell Disease") are at Rockefeller University. Cerami, who heads Rockefeller's laboratory of medical biochemistry, began his career in the field of agriculture, receiving his B.S. from the Rutgers University College of Agriculture in 1962. Thereafter he became interested in biochemistry, and he obtained his Ph.D. in that field in 1967. He spent one year as a postdoctoral fellow at the Harvard Medical School and another at the Jackson Laboratory before joining the Rockefeller faculty in 1969. Peterson, a 1965 graduate of Carleton College, was awarded an M.D. by the Columbia College of Physicians and Surgeons in 1969. After a year on a fellowship in Bolivia he continued his medical training at Harlem Hospital, where his concern for patients with sickle-cell disease was aroused. In addition to his teaching and research Peterson works as a physician at both Harlem Hospital and New York Hospital.

ROBERT T. BAKKER ("Dinosaur Renaissance") is a member of the Society of Fellows at Harvard University, associated primarily with the Department of Geology and the Museum of Comparative Zoology. His research ranges over several fields, focusing mainly on "the intersection of physiology, ecology and geology." After graduating from Yale College in 1967 Bakker developed educational projects for elementary school children at Yale's Peabody Museum of Natural History, did free-lance illustrating for a year and carried on "informal" investigations at Yale of the ecology and life-styles of fossil animals. He went to Harvard as a graduate student in 1971 and was elected a Junior Fellow two years later.

PETER ALBERSHEIM ("The Walls of Growing Plant Cells") is a professor at the University of Colorado, where he teaches courses in biochemistry, molecular genetics and general biology. He majored in plant pathology and chemistry as an undergraduate at Cornell University and acquired his Ph.D. in biochemistry from the California Institute of Technology in 1959. After a postdoctoral year as a research fellow at the Swiss Federal Institute of Technology he taught for four years at Harvard University before moving to Colorado in 1964. The primary objective of his work, he writes, "is to see our basic research have a significant impact on the social and economic problems involved with feeding the world's people. Toward this end our laboratory has been for many years heavily involved in trying to understand the molecular basis for disease resistance in plants and, more recently, in studying the host selectivity of nitrogen-fixing bacteria."

C. M. YONGE ("Giant Clams") is a marine biologist at the University of Edinburgh, where he studied as an undergraduate and a graduate student in the 1920's. Before returning to his alma mater in 1970, Yonge worked for many years as professor of zoology at the universities of Bristol and Glasgow and as an investigator "at marine-research stations all over the world." His interest in the giant clams and other tridacnids originated during a 13-month stint as leader of the Great Barrier Reef Expedition of 1928–1929. A prolific author of books and papers on a variety of topics in marine biology, Yonge reports that in spite of his age (he is 75) "I have never been more vigorously active in research and writing." He was elected a Fellow of the Royal Society in 1946 and was knighted in 1967. His main outside interest is history. "I read far more history than I do biology," he writes, adding that "I like to think I may be the only person to have read Gibbon's *Decline and Fall* from first word to last on a coral reef."

ROBERT HOWARD ("The Rotation of the Sun") is a staff member of the Hale Observatories of the Carnegie Institution of Washington and the California Institute of Technology. The observations for his research come primarily from the Mount Wilson Observatory, where he is responsible for the solar-research program. Howard has been associated with Mount Wilson since receiving his doctorate from Princeton University in 1957, except for two years spent as an assistant professor at the University of Massachusetts from 1959 to 1961.

HUGH J. McQUEEN and W. J. McGREGOR TEGART ("The Deformation of Metals at High Temperatures") are respectively professor of materials science at Concordia University in Montreal and research manager of the Broken Hill Proprietary Company in Melbourne. McQueen did his undergraduate work at McGill University and received his Ph.D. from Notre Dame University in 1961. His primary interests are teaching mechanical metallurgy and conducting research in the hot-working of metals. Tegart did his undergraduate studies at the Royal Melbourne Institute of Technology and received his Ph.D. from the University of Sheffield in 1959. He taught metallurgy and directed research in the creep and hot-working of metals at Sheffield and was later professor of materials at the College of Aeronautics in Cranfield. He returned to his native Australia to join the Broken Hill Company in 1968.

Established 1845 SCIENTIFIC AMERICAN April 1975 Volume 232 Number 4

# The Proliferation of Nuclear Weapons

*Unless the major nuclear powers begin to live up to their obligations under the Nonproliferation Treaty, it seems likely that a large number of near-nuclear countries will emulate India and join the "nuclear club"*

by William Epstein

Next month, five years after the entry into force of the Treaty on the Nonproliferation of Nuclear Weapons, the representatives of the 84 nations that are party to the agreement will meet in Geneva in fulfillment of a pledge "to review the operation of this Treaty with a view to assuring that the purposes of the Preamble and the provisions of the Treaty are being realized." How well has the Nonproliferation Treaty worked toward the accomplishment of its stated goals? It is hard to escape the conclusion that it has failed in almost every important respect.

The magnitude of this failure was emphasized last May by India's successful underground test explosion of a "peaceful" nuclear device. Now that India, a poor, underdeveloped country, has joined the other five nuclear powers in demonstrating its potential for making nuclear weapons, one can hardly expect that membership in what once seemed to be an exclusive "nuclear club" can be held to six.

The roots of the failure of this arms-control effort, however, go deeper. The preamble and the provisions of the Nonproliferation Treaty call for, among other things, the discontinuance of all nuclear-weapons tests, the cessation of the nuclear-arms race, the enactment of effective measures in the direction of nuclear disarmament and the commitment of the nuclear powers to make available the benefits of the peaceful applications of nuclear technology (including nonmilitary nuclear explosives) to all parties to the treaty. Nothing seems clearer than that the major nuclear powers—in particular the U.S. and the U.S.S.R., both of whom (unlike India) signed and ratified the treaty—have failed to live up to those obligations. How has this situation come about? And what can be done at this late stage to prevent things from getting even worse?

Let us begin by considering what the Indian nuclear explosion means, both in terms of the proliferation of nuclear weapons and in terms of the structure of international relations. First of all, it is important to realize that there is no essential technological difference between a nuclear explosive intended for peaceful purposes and one intended for waging war. The same device that blew a hole in the earth under the Rajasthan desert and left a large crater on the surface could just as well wipe out a city and its inhabitants. Indeed, the explosive yield of the Indian device, estimated to be equivalent to from 15 to 20 kilotons of TNT, was of the same order as the yield of the bombs that destroyed Hiroshima and Nagasaki. The main difference was in the ostensible purpose of the explosion. Indian government officials have repeatedly declared that their explosion was for peaceful purposes only and that India has no intention of developing nuclear weapons. Intention is a subjective matter based on a unilateral decision, however, and as such it can be changed at will, with or without notice. Thus in the absence of any binding legal commitment there is nothing to prevent the Indian government from changing its mind whenever it wants to. Even if one fully accepts the Indian declaration of intention to use nuclear explosions exclusively for peaceful purposes, the plain fact is that India's nuclear devices can also be used as nuclear weapons whenever India so decides. Other powers can only regard India's peaceful nuclear devices as nuclear weapons. Henceforth, in spite of repeated protestations by the Indian government, India must be regarded by other powers as being not only a nuclear power but also a nuclear-weapons power. This perception will be regarded as all the more valid in view of the fact that a public-opinion poll taken in India soon after the explosion showed that two-thirds of the Indian people favored India's making nuclear weapons.

The Indian test explosion has also shown the way for other nations to "go nuclear" under the guise of testing devices for peaceful purposes. Any one of the potential nuclear powers that has not become a party to the Nonproliferation Treaty can emulate India's example. Even countries that are party to the treaty retain this option, since the text of the treaty provides that any party can withdraw on three months' notice.

It is much easier for a government to assuage both domestic and international opinion by proclaiming its intention to conduct nuclear explosions solely for peaceful purposes than to say outright that it intends to make nuclear weapons. Nuclear weapons are, after all, still regarded with abhorrence as weapons of mass destruction. All the first five nuclear-weapons states have declared that they produced nuclear weapons solely for defense and not for aggression. One can now look forward to a new chapter in the nuclear story, where countries that want to become nuclear-weapons states, for whatever reason, would first go through the stage of producing nuclear devices for "peaceful" purposes. This cosmetic façade would be sufficient to enable a moderately advanced nation over a period of time to produce a wide range of nuclear warheads.

The Indian leaders insist that they broke no law, treaty or agreement in conducting the Rajasthan test, and they are right. The Partial Test-Ban Treaty of 1963, to which India is a party, bans tests in the atmosphere, in outer space and underwater, but it does not ban them underground. The only restriction on underground tests is against those that vent and carry radioactive debris beyond the territory of the country where the test is held. Several tests conducted by both the U.S. and the U.S.S.R. have vented and carried radioactive debris beyond their borders, but these were regarded as mere "technical violations" of the treaty since they were accidental in the sense that no violation was intended or expected. It would appear, however, that there was no violation, technical or otherwise, as a result of the Indian test.

The Nonproliferation Treaty is the only international instrument that bans the explosion of nuclear devices for peaceful purposes by states that do not have nuclear weapons. The transfer or acquisition of "nuclear weapons or other nuclear explosive devices" is specifically banned for non-nuclear-weapons states by Article II of the treaty. Peaceful nuclear explosions, however, to be conducted only by nuclear-weapons states under an appropriate international regime for the benefit of non-nuclear-weapons states, are expressly envisioned by both the preamble and Article V of the treaty. India is in any case not a party to the Nonproliferation Treaty. In fact, both during and after the negotiation and conclusion of the treaty, India publicly announced its opposition to the accord as discriminatory and unfair, and declared that it reserved the right to conduct its own nuclear explosions for peaceful purposes. Hence India cannot be accused of any breach of either the letter or the spirit of the Nonproliferation Treaty.

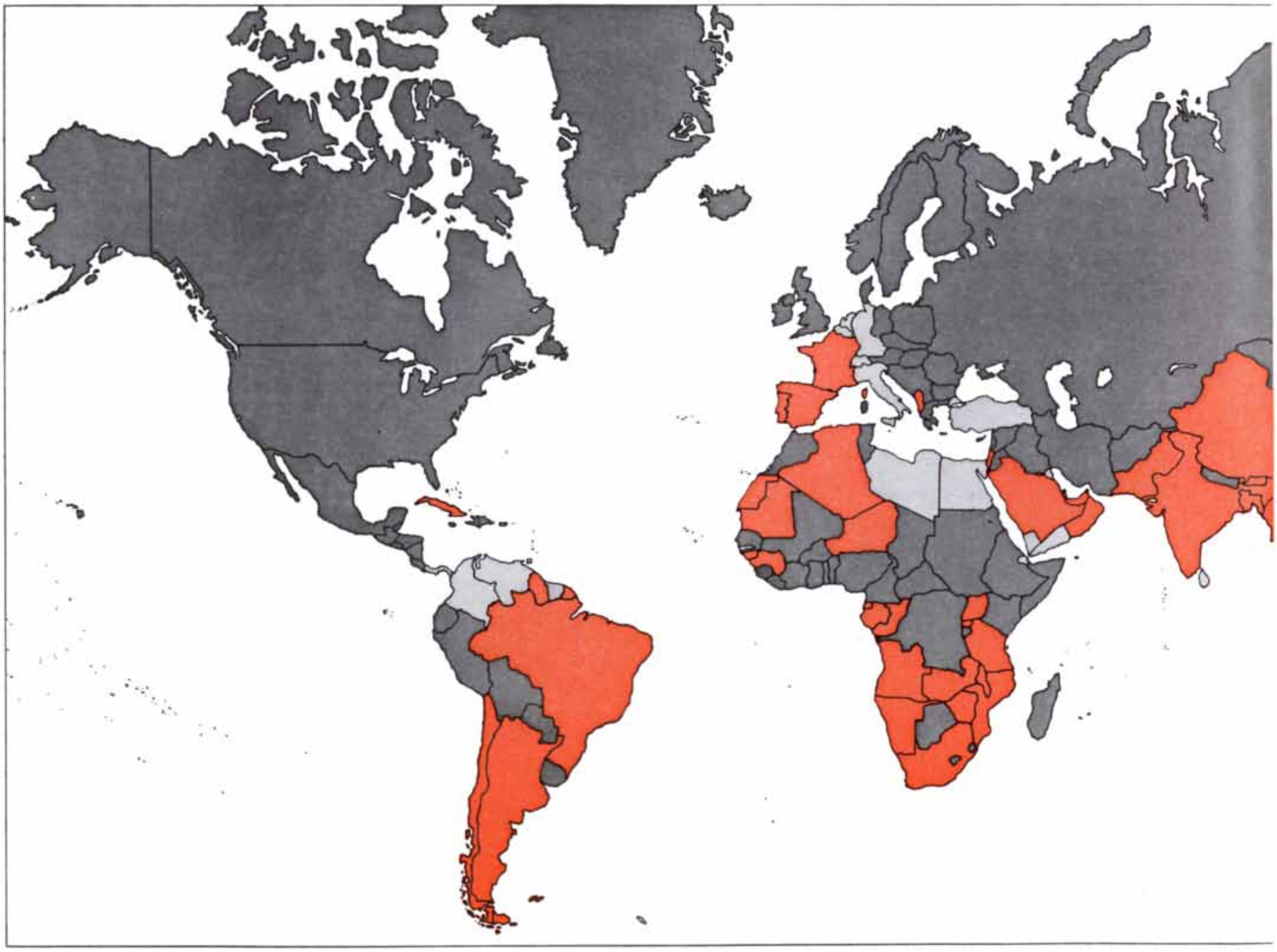
On the other hand, India is a party to and an active participant in the work of the International Atomic Energy Agency (IAEA) in Vienna. The statute of that agency, which went into force in 1957, specifically bans the use of atomic energy "in such a way as to further any military purpose" but positively encourages "the development and practical application of atomic energy for peaceful purposes." A number of United Nations and IAEA conferences from 1958 to 1971 held out high hopes for the potential benefits that would be obtained from nonmilitary nuclear explosions. These benefits may be largely illusory or downright mythical, but there can be no doubt that over the years nuclear and non-nuclear powers alike were dazzled by the glittering prize that could be theirs when nonmilitary nuclear explosions became

**CRATER formed by India's underground nuclear explosion on May 18, 1974, appears in this aerial photograph released by the Indian Department of Atomic Energy. The test was conducted "for peaceful purposes" at a site in the Rajasthan desert east of New Delhi. The yield of the device was between 15 and 20 kilotons, approximately the same as the yield of the Hiroshima bomb.**

feasible. Although the nuclear-weapons states are apparently becoming increasingly disenchanted by their failure to achieve any important technical or economic objectives after investing years of effort and hundreds of millions of dollars in testing nonmilitary nuclear explosives, the poorer nations of the world seem to regard such devices as the key that could help them to unlock the door to great industrial and engineering undertakings at little cost. As recently as July, 1974, in the Threshold Test-Ban Treaty signed by Secretary Brezhnev and President Nixon in Moscow, specific provision is made for entering into a new bilateral agreement for the exchange of data about nonmilitary nuclear explosions at the earliest possible time. Thus India can hardly be criticized for wanting to achieve what was not prohibited for it by any international treaty or agreement and what was given the specific blessing of a number of international treaties and studies.

Regardless of what one may think of India's tactics and behavior, and convinced as one may be that India will eventually turn its peaceful nuclear devices into nuclear weapons, its declared intention to use these devices exclusively for peaceful purposes cannot be disproved. One can only regret that the nation of Gandhi and Nehru (who first proposed the end of nuclear testing in 1954) may be responsible for undermining efforts to prevent the proliferation of nuclear weapons. One might also be allowed to doubt the wisdom–in terms of India's own ultimate political, economic and military interests–of its having decided to go nuclear.

Public reactions to the Indian explosion have been rather few and mixed. Not a word of criticism has been heard from the two Asian nuclear powers, China and the U.S.S.R. China has attacked the Nonproliferation Treaty from its inception as a device by the two superpowers to maintain their nuclear hegemony and to dominate the non-nuclear states. The Chinese have for many years in effect advocated the proliferation of nuclear weapons as a means whereby the underdeveloped countries of the "Third World" could protect themselves from nuclear threats and blackmail by the nuclear superpowers. In any event it is unlikely that India can become a threat to China in the foreseeable future, even if India decides to become a nuclear-weapons power. Nevertheless, in view of India's close relations with the U.S.S.R. and the fact that India was clearly the strongest military power in southern Asia even before last May, China can hardly regard India's growing nuclear power with equanimity. In the context of Chi-



**CURRENT STATUS OF NONPROLIFERATION TREATY is depicted on this world map. The 84 nations that are full parties to the agreement are shown in dark gray. The 22 nations that have signed the treaty but have not yet ratified it, and hence are not bound by**

nese and Indian relations with other Asian countries and the Third World, and in particular with Pakistan, with whom China has close and friendly relations, the political implications of the Indian explosion are of greater importance than the military ones. Moreover, if Taiwan, which is a party to the Nonproliferation Treaty, should be encouraged by the Indian example to withdraw from the treaty and go nuclear, this would pose some new and difficult problems for China. It is also difficult to believe that China would be completely unconcerned if South Korea, Indonesia, Iran or Australia were also to go nuclear. The official silence from Peking, which is itself conducting tests in the atmosphere, may therefore mean only that China has not yet worked out its final position with respect to the Indian explosion or is biding its time pending a clarification of Third World opinion.

**its provisions, are in light gray. The 38 nonsignatories (among them India) are in color.**

On the other hand, the U.S.S.R., which together with the U.S. was the chief protagonist of the Nonproliferation Treaty, must surely find the Indian action disquieting. Although the U.S.S.R. too has not uttered a single official word of complaint, Russian diplomats and arms-control experts have privately indicated their unhappiness. It could hardly be otherwise. It may be that a nuclear India that continues to be friendly to the U.S.S.R. provides some benefits or leverage for the U.S.S.R. with respect to China, but any such possible advantage would be far outweighed if India's action should lead to the further erosion of the Nonproliferation Treaty and to the spread of nuclear-weapons capability to other states, particularly those around the periphery of the U.S.S.R.

France, which is also conducting tests in the atmosphere, has made no official statement, although the chairman of the French Atomic Energy Commission sent a congratulatory message to the chairman of the Indian Atomic Energy Commission. The French position is anomalous. France is not a party to the Nonproliferation Treaty, but it has announced from the start that it will behave exactly as if it were a party. Nevertheless, France is busy selling nuclear reactors to a number of countries, and although these deals are subject to IAEA safeguards, as far as is known they do not bar peaceful nuclear explosions.

Great Britain, which has also been a strong supporter of the Nonproliferation Treaty, was at first strongly critical of the Indian explosion. After the initial criticism, however, little has been heard from the British, who have themselves been criticized for resuming underground testing in June, 1974, when they set off an explosion (in the U.S.) for the first time since 1965.

The U.S. was at first rather cautious in its official reaction to the Indian explosion. It did reiterate its views to the Indian government that peaceful and military nuclear explosive devices are indistinguishable, but it seems to wish to avoid any public dispute with India. Privately it has sought a commitment that plutonium produced from nuclear fuel supplied by the U.S. would not be used for any kind of explosion. Failing to receive adequate assurances, the U.S. delayed the delivery of enriched uranium to fuel the Tarapur reactor, which was built with American technical and financial assistance. At the moment it appears that India will give the necessary assurances and that the U.S. will continue supplying uranium to India.

As was to be expected, Pakistan, which signed but never ratified the 1963 Partial Test-Ban Treaty and which has not signed the Nonproliferation Treaty, immediately protested in every possible forum against the Indian explosion and called for a halt to further tests. Pakistan also announced that it would acquire a similar nuclear capability. It has proposed that the UN General Assembly discuss the creation of a nuclear-free zone in South Asia; the proposal (which India rejected) must be regarded as a tactical political move intended to make clear to the world where the blame lies.

Apart from Pakistan, only Canada, Japan and Sweden, all of which have the capability of undertaking nuclear explosions, have taken a strong public stand against the Indian test. Canada cut off all further nuclear cooperation with India almost immediately, and all three countries in statements in their capitals, in the Geneva disarmament conference, in messages transmitted to the Indian government and in the UN General Assembly deplored the Indian explosion and its possible adverse effects on international efforts to prevent the proliferation of nuclear weapons. Australia and the Netherlands have also criticized the Indian test.

As for the nonaligned and underdeveloped countries, while saying little in public, they have in large part welcomed the Indian test as a technological achievement demonstrating that even a poor country can accomplish the sophisticated task of successfully exploding an underground nuclear device, which had for a decade been the exclusive preserve of the five great powers. Yugoslavia, one of the leaders of the nonaligned countries, congratulated India on its technological achievement. Nigeria said that the Indian action was not surprising in view of the lack of progress by the nuclear powers in stopping underground nuclear tests and the nuclear-arms race.

Without the wide support of the non-nuclear-weapons states of the Third World, the Nonproliferation Treaty would never have received the overwhelming commendation of the UN General Assembly. Most of them have no significant nuclear programs and are in no position to go nuclear for several decades to come. In 1968 these countries entered into a tacit alliance with the nuclear powers, because it seemed clear that the further "horizontal" spread of nuclear weapons to the near-nuclear countries, nearly all of which were developed countries, was not in the interest of either group. The Third World countries as a group, however, were never greatly impressed by the Nonproliferation Treaty.

Many of those who decided to support the treaty did so in the dual expectation that the nuclear-weapons powers would halt the "vertical" proliferation of nuclear weapons (their further sophistication, development and deployment) and would also make available to the underdeveloped countries the benefits of the peaceful uses of nuclear energy, including nonmilitary nuclear explosions. These countries have become disillusioned by the failure of the nuclear powers to halt the nuclear-arms race and by the paucity of the benefits received from the peaceful applications of nuclear energy. They are impressed by the achievements of China and India, and some of the more advanced among them are much more receptive now to the argument, illusory though it is, that nuclear weapons are "equalizers" that would better enable them to withstand the unspoken threats of the nuclear-weapons states and promote their own security and economic development. In fact, some of the Third World countries seem to be increasingly inclined to accept the idea that the acquisition of nuclear-weapons capability by some of the near-nuclear powers would place greater restraints on the monopoly position and freedom of action of the nuclear-weapons states, and that this could bring some advantages to the Third World as a whole. At the UN General Assembly in the fall of 1974 apart from the six countries mentioned above there was practically no criticism of the Indian explosion (and none from any Third World country except Pakistan). In short, India has apparently succeeded in becoming a nuclear power with remarkably little adverse reaction.

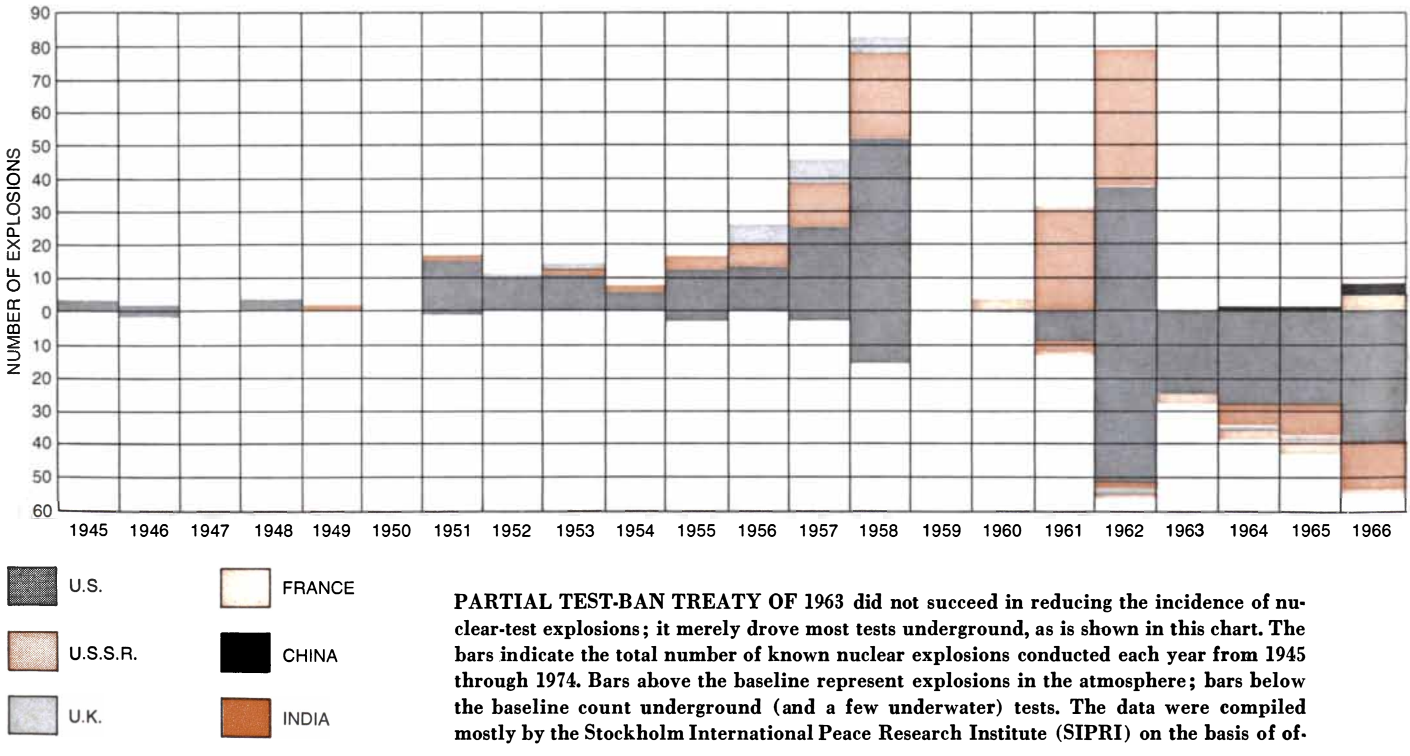
Why did India go nuclear? To be sure, India had throughout the negotiation of the Nonproliferation Treaty and after its conclusion denounced the treaty as a discriminatory instrument and had repeatedly announced that it reserved the right to conduct its own nuclear explosions for peaceful purposes. That, however, is not the whole story.

India was obviously greatly concerned by the Chinese nuclear explosion of October 16, 1964. On December 4 of that year Prime Minister Lal Bahadur Shastri, discussing the Chinese nuclear bomb, stated that all non-nuclear countries needed a guarantee by the existing nuclear powers against nuclear attack. He added that it would be "very wise" for the nuclear powers "to give serious thought to this aspect of the problem."

In May, 1965, the Indian ambassador to the UN, Birendra Narayan Chakravarty, told the Disarmament Commission that an "integrated solution" was required to solve the problem of the spread of nuclear weapons. He said: "It is no use telling countries, some of which may be even more advanced in nuclear technology than China, that they should enter into a treaty which would stipulate only that they must not acquire or produce these weapons. Again it is no use telling them that their security will be safeguarded by one or another of the existing nuclear powers. Such an assurance has to be really dependable. Unless the nuclear powers . . . undertake from now on not to produce any nuclear weapons or vehicles for weapons delivery and, in addition, agree to reduce their existing stockpile of nuclear weapons, there is no way of doing away with proliferation."

In July of the same year the Indian ambassador to the Geneva disarmament conference, Vishnuprasad Chunilal Trivedi, said that the "essential" requirement for a "rational and acceptable" treaty on nonproliferation was "tangible progress toward disarmament, including a comprehensive test-ban treaty, a complete freeze on production of nuclear weapons and means of delivery as well as a substantial reduction in the existing stocks." He added that the institution of international controls on peaceful nuclear reactors and nuclear power stations, while leaving free the vast weapon-producing facilities of the nuclear powers, was "like an attempt to maintain law and order in a society by placing all its law-abiding citizens in custody while leaving its law-breaking elements free to roam the streets."

On April 27, 1967, the Indian External Affairs Minister, Mahomedali Currim Chagla, criticized the draft nonproliferation treaty as "discriminatory" because, among other things, it sought to

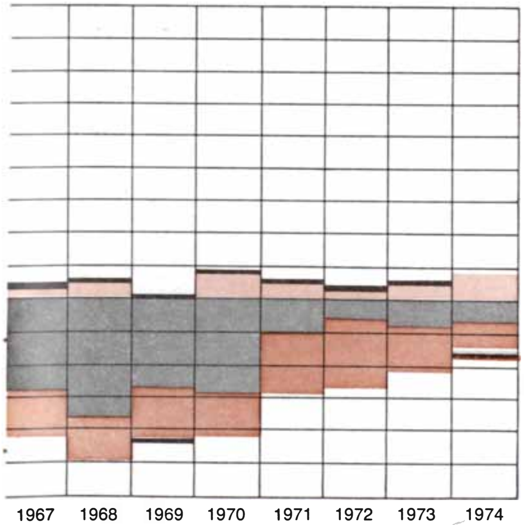



**PARTIAL TEST-BAN TREATY OF 1963 did not succeed in reducing the incidence of nuclear-test explosions; it merely drove most tests underground, as is shown in this chart. The bars indicate the total number of known nuclear explosions conducted each year from 1945 through 1974. Bars above the baseline represent explosions in the atmosphere; bars below the baseline count underground (and a few underwater) tests. The data were compiled mostly by the Stockholm International Peace Research Institute (SIPRI) on the basis of of-**

maintain the monopoly of the nuclear powers. Only the non-nuclear powers would be prevented from conducting underground explosions for peaceful nuclear research. He added that India was in a "peculiar position" because it was a nonaligned country not under the "nuclear umbrella" of any nuclear country, because it was far advanced in nuclear research and because it was under the "continuing threat and menace" of China, which had become a nuclear power. If India was not to explode a bomb, it must have a "credible guarantee" of its security.

For several years India sought effective guarantees of its security by the nuclear powers, but its efforts were in vain. Failing to obtain any adequate direct security assurances, India shifted its emphasis to the indirect approach by insisting that all the nuclear powers stop testing and manufacturing nuclear weapons and start reducing their nuclear arsenals. When this approach also seemed likely to fail, India began stressing its right and need to conduct its own peaceful nuclear explosions for economic development.

At this late stage one can only speculate that India might not have gone ahead so soon, if at all, with the explosion of its own nuclear device if it had been offered adequate guarantees of its security, and that it might have been willing to accept the protection of a joint American-Russian nuclear umbrella, as Japan seemed content to accept an American one. Unfortunately that possibility was never put to any real test. In fact, none of the main demands in India's "integrated" approach were met.




**ficial announcements and other sources. The figures do not include several dozen secret tests conducted by the U.S. and the U.S.S.R. France and China are not party to the Partial Test-Ban Treaty and hence are not legally prohibited from testing in the atmosphere.**

Are there any benefits to be gained from peaceful nuclear explosions? Ever since the discovery of nuclear fission high hopes have been held out for the potential blessings that would be conferred on mankind by the peaceful uses of nuclear energy and technology. At first attention was devoted to the benefits from power reactors and from the use of radioactive isotopes in science, medicine, industry and agriculture. It was only after the U.S. Atomic Energy Commission launched its "Plowshare" program in the late 1950's that interest developed in peaceful nuclear explosions. At that time great engineering projects were visualized: the digging of canals, harbors and so forth. Those ideas were soon discarded by the U.S. when the dangers of radioactivity from cratering explosions became apparent. Interest then turned to the idea of fracturing oil-bearing or gas-bearing rock by underground nuclear explosions in order to stimulate the flow of oil and gas; the idea of blasting underground cavities for their storage was also promoted, as was the idea of leaching minerals, such as copper ore, by such means. None of the American underground explosions has been successful in achieving any of these goals. It has become apparent that to succeed in fracturing rock to produce substantial quantities of oil and gas not one explosion or two but hundreds or even thousands would be required. Such operations would be extremely costly as well as hazardous, and no practical way of dealing with the radioactive by-products has yet been discovered.

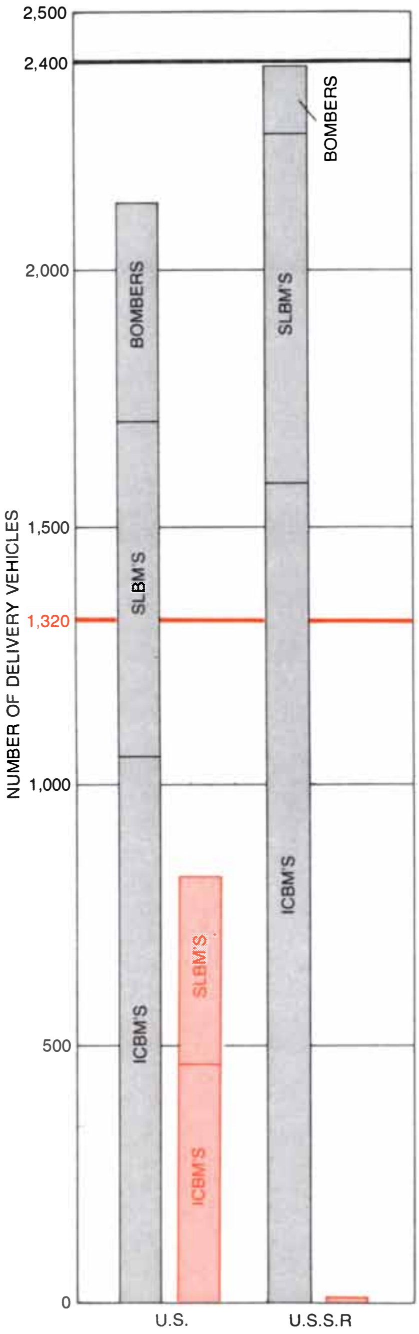
Curiously enough, as American nuclear experts began to lose interest in the peaceful uses of underground explosions and to doubt whether they had any practical end that could not be achieved as well or better by ordinary high explosives or by other conventional means, their Russian counterparts began to show greater interest in them. They spoke of achieving the same goals as the Americans had at an earlier stage and added some new ideas of their own. In the past few years they have suggested diverting water flowing to the Arctic Ocean by means of a canal to the Volga River and thence to the Caspian Sea. This would require from 250 to 400 cratering explosions, with all the hazards attending the release of huge amounts of radioactivity. The U.S.S.R. was successful in throwing up a dam to create a lake and in putting out, by means of underground explosions, two runaway gas-well fires that had been out of control for more than a year, but here too it is not clear that the jobs could not have been done better with high explosives. Apparently the U.S.S.R. has been no more successful than the U.S. in increasing the flow of oil and gas or in the extraction of minerals by means of nuclear explosions.

Within the past year there has been increasing evidence that the U.S.S.R. is also becoming disillusioned by its inability to fulfill the expectations it once had for the benefits from peaceful nuclear explosions. Although it was the U.S.S.R. that insisted on the inclusion in last year's Threshold Test-Ban Treaty of the article providing for an agreement governing such tests, in private Russian scientists have been stating quite freely their opposition to nonmilitary nuclear explosions because of their harmful rather than beneficial potential.

Some American experts hold the view that there never was a good case for peaceful nuclear explosions, and that the idea was fostered and publicized in the U.S. by the very scientists who wished to promote the military rather than the peaceful applications of nuclear energy; in other words, that the campaign on behalf of peaceful nuclear explosions was conducted as a stratagem, somewhat similar to the campaign for "clean" nuclear weapons, to prevent or circumvent any agreement to ban or halt underground nuclear-weapons tests.

Be that as it may, those who were promoting the potential benefits of nuclear explosions were most successful in promoting their ideas. Three international conferences on the Peaceful Uses of Atomic Energy sponsored by the UN and the IAEA in 1958, 1964 and 1971 stressed the importance of nonmilitary nuclear explosions and the encouraging prospects for them. The same conclusions were drawn by an international group of experts convened by the UN Secretary-General in 1969 at the request of the non-nuclear-weapons states that were interested in an impartial report on the possible peaceful uses of nuclear energy. These conclusions and results were again confirmed by three international panels of experts (mostly American and Russian) convened by the IAEA in 1969, 1970 and 1971. Thus it is not surprising that the underdeveloped countries hold out such high hopes for the potential benefits they will receive from nonmilitary nuclear explosions, or that India has now revived the old arguments.

Nevertheless, in the past two years the evidence from the tests conducted by both the U.S. and the U.S.S.R. leads to




**CEILINGS** imposed on the numbers of the strategic nuclear weapons of the two superpowers as a result of their Vladivostok "understanding" of November, 1974, are clearly higher than either country's present strength. Gray bars indicate the total number of strategic delivery vehicles deployed at present by each side; the bars are broken down into land-based intercontinental ballistic missiles (ICBM's), submarine-launched ballistic missiles (SLBM's) and heavy bombers. Colored bars indicate number of missiles equipped with multiple independently targetable reentry vehicles (MIRV's). The Russians have just begun to install MIRV's on some of their land-based missiles. By the terms of the Vladivostok agreement, which runs until 1985, each side is allowed to have no more than 2,400 strategic delivery vehicles, of which 1,320 can be armed with MIRV's.

more doubts than answers, from both the technical point of view and the economic. If the potential benefits elude the highly industrialized and technically sophisticated nuclear-weapons powers, they would seem to be even more remote and more questionable for a country that is still in the developing stage with respect to both industry and nuclear technology. This is an additional reason why many experts look with suspicion on the Indian test as a public peaceful cloak for a private military purpose.

No other question in the field of arms control and disarmament has been the subject of so much study and discussion as the question of stopping nuclear-weapons tests. Ever since Prime Minister Nehru called for a halt to such tests in 1954 the subject has been at or near the top of the disarmament agenda.

By the Partial Test-Ban Treaty of 1963 the nuclear powers undertook to seek "to achieve the discontinuance of all test explosions of nuclear weapons for all time" and expressed their determination "to continue negotiations to this end." That commitment was repeated in the Nonproliferation Treaty. One measure of its implementation can be found in a comparison of nuclear-weapons tests before and after the signing of the Partial Test-Ban Treaty [*see illustration on preceding two pages*].

After the signing of the Partial Test-Ban Treaty there were in fact no serious discussions between the two main nuclear powers on an underground-test ban for more than a decade, in spite of many resolutions adopted by the UN General Assembly every year calling for a comprehensive test ban. The non-nuclear powers appear to regard an underground-test ban as a litmus test of the seriousness of the intentions of the two superpowers to stop the nuclear-arms race. Although such a halt would not by itself end the further technological improvement of nuclear weapons, it would be an important step in that direction. There is an increasing conviction among the nations of the world that a ban on underground tests is the single most important measure, and certainly the most feasible one in the near future, toward halting the nuclear-arms race. They also seem to regard an underground-test ban by the U.S. and the U.S.S.R. as possibly having a beneficial effect on persuading China and France to curb and ultimately halt their testing. It would certainly put the superpowers in a better moral position to urge the non-nuclear countries that are capable of going nuclear to resist the temptation to do so.

The Threshold Test-Ban Treaty agreed to by the U.S. and the U.S.S.R. in Moscow last year allows the parties to continue unrestricted underground tests of whatever size they wish until March 31, 1976; thereafter they will limit weapon tests to 150 kilotons each, which is about 10 times larger than the yield of the bomb that was dropped on Hiroshima and which exceeds in size all but a few of the tests conducted in recent years [*see illustration on pages 26 and 27*]. No limitation whatsoever was put on underground explosions for peaceful purposes. This is not just a cosmetic agreement; it is a mockery of a test-ban treaty. Indeed, it may be harmful to the cause of nuclear nonproliferation. It will not help to curb the qualitative improvement, testing and development of new nuclear weapons. Therefore it will not serve to halt the nuclear-arms race. And it will not alleviate the concerns or satisfy the demands of the non-nuclear powers or provide any cogent reason for them to forbear from testing.

The delayed threshold ban has led some interested non-nuclear powers to conclude that once again they were being misled by the nuclear superpowers and that there was no early prospect of any real action to stop the nuclear-arms race. The same can be said of the strategic-arms-limitation talks (SALT). On the day of the signing of the Nonproliferation Treaty (July 1, 1968) it was announced that the U.S. and the U.S.S.R. would begin bilateral discussions on the "limitation and reduction of both offensive and defensive strategic-nuclear-weapon delivery systems." The SALT meetings did not begin until November, 1969. In May, 1972, the U.S. and the U.S.S.R. at the summit meeting in Moscow signed the Treaty on the Limitation of Anti-Ballistic-Missile Systems and also an Interim Agreement on Certain Measures with Respect to the Limitation of Strategic Offensive Arms. Under the ABM treaty each of the parties agreed to deploy no more than 100 ABM launchers and 100 missiles at each of two launch sites in both countries. They also agreed to certain limitations on their ABM radars, but modernization and replacement of ABM systems was allowed. Under the Interim Agreement on Offensive Arms, which has a duration of five years, the U.S. is entitled to increase the number of its nuclear submarines from 41 to 44 with 710 nuclear missiles, and the U.S.S.R. is entitled to build up to 62 submarines carrying 950 nuclear missiles; the U.S. can also retain 1,000 land-based intercontinental missiles and the U.S.S.R. can retain 1,410. No limitation was placed on installing multiple independently targetable reentry vehicles (MIRV's) on either sea-based or land-based missiles.

Last year's Summit III meeting in Moscow also did little to halt or reverse the nuclear-arms race. The two parties agreed to restrict their ABM's to only one site each instead of the two allowed under the 1972 agreement. (The new agreement is practically without significance, since neither party intended to build a second site anyway.) There was complete failure to reach any agreement to limit offensive strategic weapons.

The Vladivostok understanding of November, 1974, was hailed as a "breakthrough" that put a "cap" on the strategic-arms race. It incorporated the interim agreement and fixed a ceiling on the number of all strategic nuclear weapons until December 31, 1985, on the basis of equality between the two superpowers. Each side is allowed to have 2,400 strategic delivery vehicles, including land-based intercontinental ballistic missiles (ICBM's), submarine-launched ballistic missiles (SLBM's) and heavy bombers. Of that number 1,320 may be armed with MIRV's. The agreement was said to establish ceilings well below the levels that otherwise could be expected in 10 years. The ceilings established, however, are clearly higher than the levels each side has at the present time, and even higher than those envisioned for 1977 under the interim agreement.

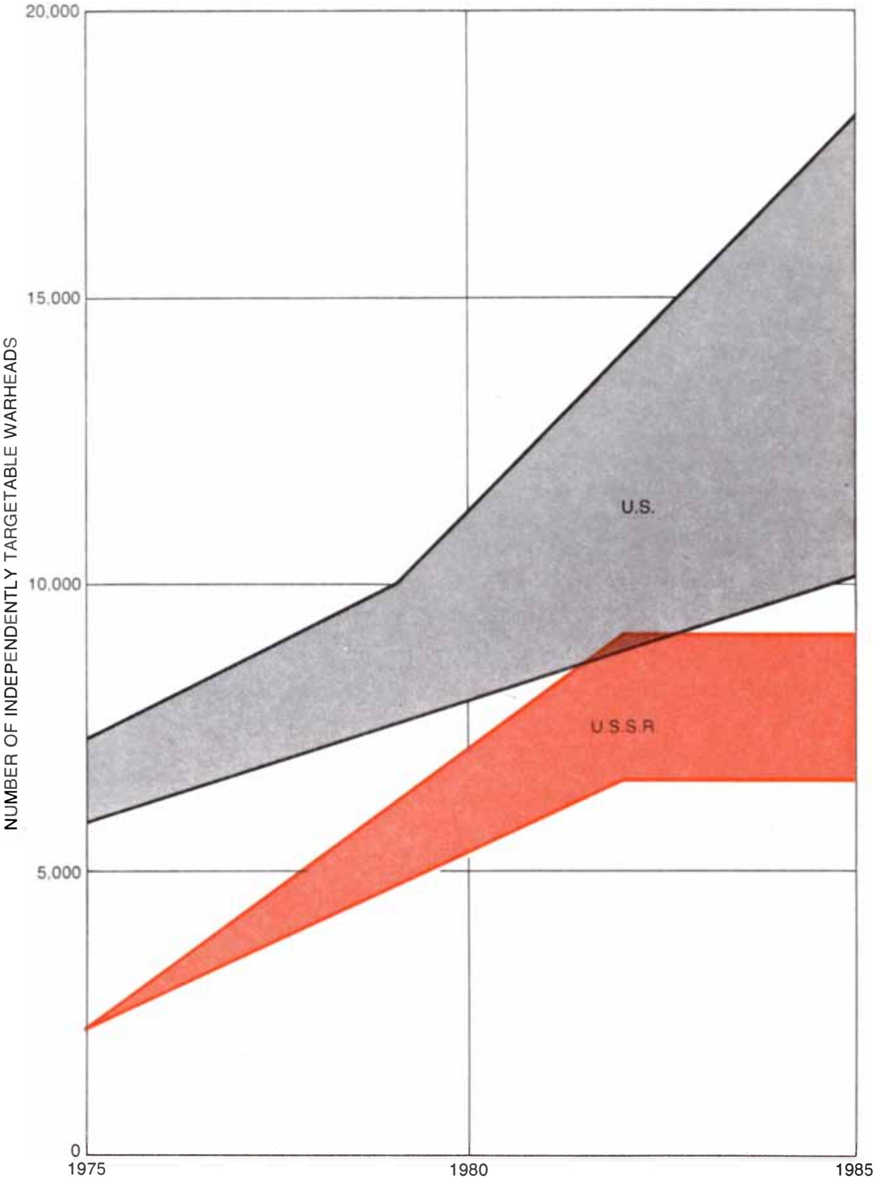
The ceiling of 1,320 MIRV's is also much higher than either country's present strength. The U.S., for example, has announced that it intends to fit 550 land-based Minutemen with three warheads and 496 Poseidon missiles with from 10 to 14 warheads, for a total of 1,046 missiles with multiple warheads. At present it has about 800 multiple-warhead missiles. The ceiling of 1,320 therefore represents not only a higher level than the U.S. now has but also a higher level than it apparently had ever planned to have.

Meanwhile the U.S.S.R. has tested and is beginning to deploy its MIRV's. It has also developed several new missiles with multiple warheads. It has not announced how many of its land-based or sea-based missiles it intends to equip with multiple warheads, but 1,320 obviously represents a high and costly ceiling that will take several years to reach.

The Vladivostok agreement put no limit on either the number of warheads that can be carried by each missile or on the size of the warheads. Since it is generally believed the Russian warheads are bigger than the American ones, there will be pressures for the U.S. to increase the size or number of its warheads. The agreement also puts no limitation on the modernization of missiles by improving their accuracy and maneuverability.

In December of last year Secretary of Defense Schlesinger said that he foresaw a need for larger and restructured strategic forces for the U.S. as a result of the Vladivostok agreement, including 12 instead of 10 of the giant Trident submarines (which together would carry 288 missiles, each with 14 warheads, for a total of 4,032 warheads), larger intercontinental missiles with MIRV's and the new B-1 bomber. This program, he said, would call for "some upward adjustment" in the strategic-arms budget.

It is clear that the "limitation" envisioned by the Vladivostok agreement,




**POSSIBLE FUTURE LEVELS of independently targetable strategic nuclear warheads allowed under the Vladivostok accords are estimated conservatively in this graph, which is based on material that appeared originally in *Arms Control Today*, a publication of the Arms Control Association. U.S. warheads are represented in gray, Russian warheads in color. The graph reflects the results of current strategic-weapons programs and projects these programs through 1985 on the assumption that they will be revised in order to build force levels up to the Vladivostok ceilings. Shaded areas suggest range of options. Not included in the projections are future U.S. bomber levels, the possible deployment on both sides of strategic cruise missiles, possible increases in the number of MIRVed warheads per missile or changes in present Defense Department estimates of the likely MIRV capabilities of the new Russian ICBM's. Multiple warheads that are not independently targetable are counted on the basis of one warhead per missile. The graph does not take into account the thousands of medium-range nuclear weapons deployed by both sides in Europe.**

although it will put an eventual cap on the number of strategic nuclear weapons, allows an expansion in both the quantitative nuclear-arms race and the qualitative one. Since no limit is fixed for the number and size of warheads on the 1,320 missiles with multiple warheads or of nuclear arms carried in bombers, each of the two superpowers can emplace 20,000 or more strategic nuclear warheads under the agreement. This immense "overkill" capacity can be measured by the estimate made about a year ago that the U.S. at that time had enough strategic weapons to destroy 36 times all 218 Russian cities with a population of more than 100,000.

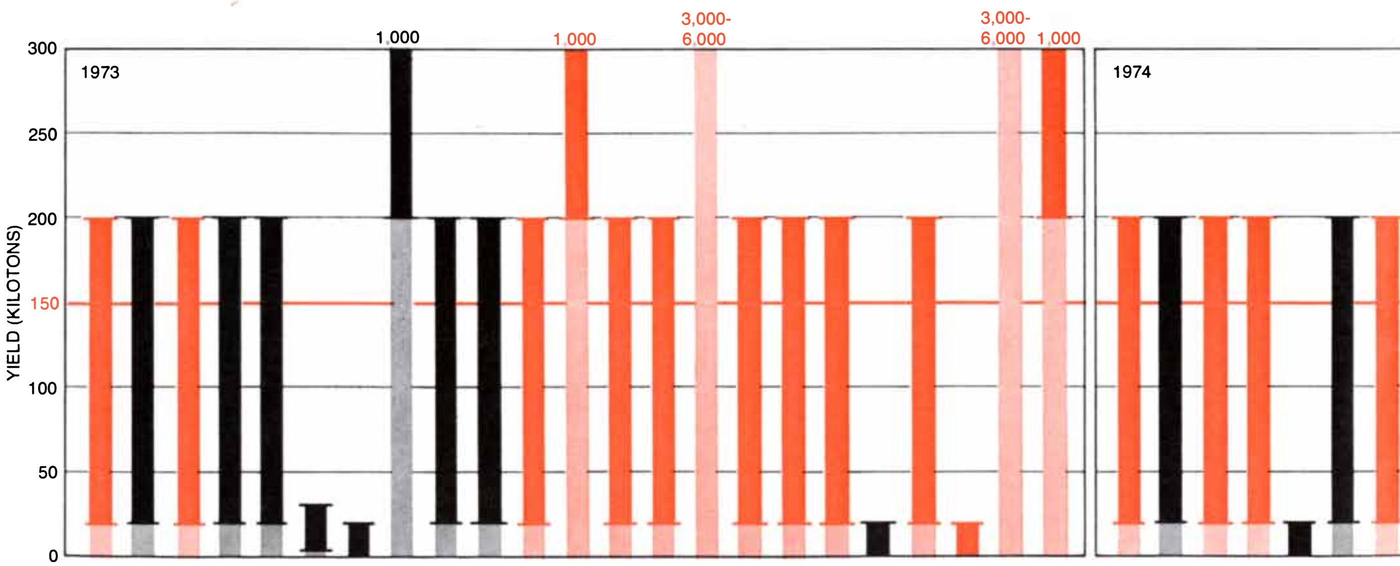
One of the reasons given for maintaining such an unconscionably high overkill capacity is the "counterforce" argument. According to that argument, strategic nuclear arms should not be programmed primarily for the task of knocking out cities and their populations but rather should be aimed at military targets such as missile silos, ammunition dumps, nuclear bases and so on. For that purpose two or more warheads are needed for each target; in addition enough arms must be kept in reserve for a second strike against the other side's cities in case it launches a large-scale first strike. What this argument conveniently overlooks is that a nuclear exchange of such magnitude would poison most of the inhabitants of the Northern Hemisphere with radioactive fallout. In either case, whether a nuclear exchange involved cities or nuclear targets, it would constitute a form of international suicide.

In addition to MIRV's the U.S. is currently developing a new maneuverable missile called MARV, and there is talk in both the U.S. and the U.S.S.R. of building mobile intercontinental missiles, even though the U.S. announced at the time of SALT I that it would regard the building of such weapons as being contrary to the spirit of the SALT I agreements. The U.S. is also proceeding to develop a shorter-range (1,500-mile) cruise missile that could be launched from aircraft, submarines or surface vessels. Further international negotiation may be needed to decide whether or not these missiles will be considered strategic weapons.

The SALT agreements, in short, may have been a diplomatic success in that they tend to stabilize mutual deterrence between the two superpowers, at least for the present, on the basis of each side's retaining a second-strike capability, but they have not served to achieve a cessation or any real limitation of the nuclear-arms race. In fact, many critics of SALT's lack of achievement say that these negotiations have only served to replace the quantitative arms race with an even more dangerous qualitative one. It seems that the agreements already concluded, and indeed those now being negotiated, are designed not to halt or reverse the arms race but rather to institutionalize and regulate it. They can, in fact, be regarded as blueprints for the continuation of the nuclear-arms race by the two superpowers.

The picture that emerges from these agreements is hardly likely to reassure the other nations of the world, nuclear as well as non-nuclear, that the arms race is being brought under control or that their security is being enhanced. The failure of the SALT negotiations to produce any real limitation or reduction of offensive strategic nuclear weapons, and the expansion of the arms race that will result from the Vladivostok agreement, will only serve to confirm the fears of the non-nuclear states that the nuclear powers are unwilling or unable to halt the nuclear-arms race.

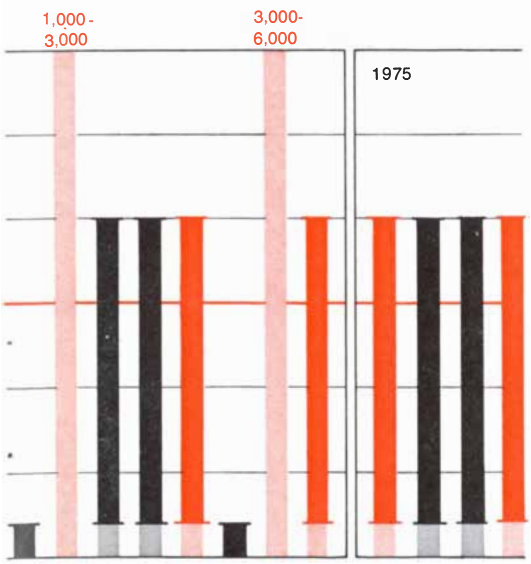
The continuing credibility and viability of the Nonproliferation Treaty was in question even before India exploded its nuclear device. The failure of the nuclear superpowers to live up to their commitments under that treaty is likely to give added force to the arguments of those in the near-nuclear countries who, for a variety of reasons, also want to go nuclear. Some of the criticisms voiced by India were echoed by Japan when the text of the Nonproliferation Treaty was approved in 1968. The Japanese ambassador to the nonproliferation talks, Senjin Tsuruoka, warned: "Unless the nuclear-weapons states keep their part of the bargain... the treaty will lose its moral basis." And when the treaty went into force in 1970 Prime Minister Wilson of Great Britain said: "We know that




**MOST UNDERGROUND NUCLEAR TESTS conducted by the U.S. and the U.S.S.R. in recent years have had yields well within the limit of 150 kilotons set in last June's Threshold Test-Ban Agreement. These bars, black for U.S. explosions and solid color for Russian ones, are based on data released by the U.S. Energy, Resources and Development Agency (formerly the Atomic Energy Commission), which announces yields only in terms of very broad ranges. Independent seismic evidence, obtained by the Research Institute of the Swedish National Defense, suggests that the yields of the great majority of tests in the announced range of 20**

there are two forms of proliferation, vertical as well as horizontal. The countries ... which are now undertaking never to possess [nuclear weapons] have the right to expect that the nuclear-weapons states will fulfill their part of the bargain."

Talk of the "*n*th-country problem" had gone out of fashion during the decade that had passed since China exploded its first nuclear device in 1964. After all, it was argued, France (which went nuclear in 1960) and China were great powers, if not as great as the two superpowers, then at least in a class with Great Britain. In any case, all five—and only these five—were permanent members of the Security Council and, as such, were given a special status under the UN Charter. Japan and West Germany were also great powers, but they were special cases as defeated enemy powers in World War II. Canada, Italy and Sweden were highly developed near-nuclear countries that could easily go nuclear, but they had no desire to do so if the nuclear club was confined to five members, and no need to do so since, with the exception of Sweden, they were protected by the American "nuclear umbrella." As for the rest of the world, although there were several countries with the potential of going nuclear, such as India and Israel, it was asserted that they were either too poor or too small and that they faced no serious immediate threat from their neighbors, such as might impel them to undertake an intensive program to become a nuclear-weapons state.




**to 200 kilotons are toward the lower end of that range. The 150-kiloton restriction is not scheduled to go into effect until next year. Moreover, "peaceful" explosions may be excluded altogether from the final agreement.**

Surprisingly, it was the nonaligned non-nuclear states that had first proposed the nonproliferation of nuclear weapons: Ireland in 1958, followed by Sweden in 1961 and India in 1962. The U.S. and the U.S.S.R. were at first reluctant but finally came to see that it was even more in the interests of the nuclear powers to prevent the spread of nuclear weapons to additional countries. The idea took hold in the 1960's and finally culminated in the compact between the nuclear and the non-nuclear powers that was formalized in the Nonproliferation Treaty. The non-nuclear-weapons states agreed not to acquire or manufacture nuclear weapons or other nuclear explosive devices in exchange for the promise on the part of the nuclear-weapons powers to assist them in exploiting the peaceful uses of nuclear energy and to end the nuclear-arms race. A number of potential nuclear powers did not sign the treaty, including India, Pakistan, Israel, Spain, South Africa, Argentina and Brazil. Among the stated reasons for their not signing were considerations of security, the discriminatory nature of the treaty and the desire or need to develop their own capability in the field of peaceful uses of nuclear technology, including nonmilitary nuclear explosions.

Nevertheless, in the heady atmosphere of 1968, when because of the tacit alliance between the nuclear-weapons states and the least developed of the non-nuclear-weapons states the treaty was commended by the UN General Assembly by an overwhelming vote, it was felt that the danger of proliferation had been put to rest. It appeared that the momentum of a tidal wave of signatures would carry along some of the reluctant non-nuclear-weapons states and that the others would not dare to flout the opinion of the vast majority of the nations of the world. France announced that although it would not sign the treaty, it would behave exactly as though it had done so, and China was considered as comparatively unimportant and isolated. (China, although publicly supporting the idea of proliferation to Third World countries, is in fact the only nuclear power that has not provided any kind of nuclear assistance, military or peaceful, to other countries.) The U.S.S.R. was pleased that West Germany and all the North Atlantic Treaty Organization countries had agreed to sign the treaty. With the announcement, when the treaty was opened for signature on July 1, 1968, that the U.S.S.R. and the U.S. had agreed to begin the SALT negotiations, it was felt that the world was finally on the right road toward control of the nuclear-arms race.

Within four years of the entry into force of the Nonproliferation Treaty those high hopes had all but vanished. Moreover, they had vanished in spite of the settlement of the Berlin problem, the admission of China and the two Germanys to the UN, the withdrawal of American forces from Vietnam, the 1972 SALT agreements and the beginnings of a détente between the U.S. and the U.S.S.R.

The developing non-nuclear-weapons states on the whole felt that they had been cheated. They had received little in the way of assistance in exploiting the peaceful uses of nuclear energy, particularly in the area they were most interested in: nuclear reactors for the production of power. On the other hand, some of the more advanced countries (such as Italy, Japan and West Germany) that were not parties to the agreement seemed to have been treated better by the nuclear powers in this respect even though it was contrary to the terms of the Nonproliferation Treaty. Moreover, no negotiation had been started to set up an international regime to make peaceful nuclear explosions available to non-nuclear-weapons states, as was pledged by the treaty. Most disappointing of all, the nuclear-arms race was going full speed ahead. France and China continued to test in the atmosphere; the U.S. and the U.S.S.R. had not halted underground tests (on the contrary, they were conducting them at a greater rate than ever before); the Sea-Bed Treaty and the SALT agreements seemed to have been arranged more for cosmetic purposes than as real arms-control measures. On any showing, in spite of the pledges in the Nonproliferation Treaty, the arms race was proceeding apace, particularly in its technological and qualitative aspects, and the gap between the nuclear and the non-nuclear powers was steadily widening.

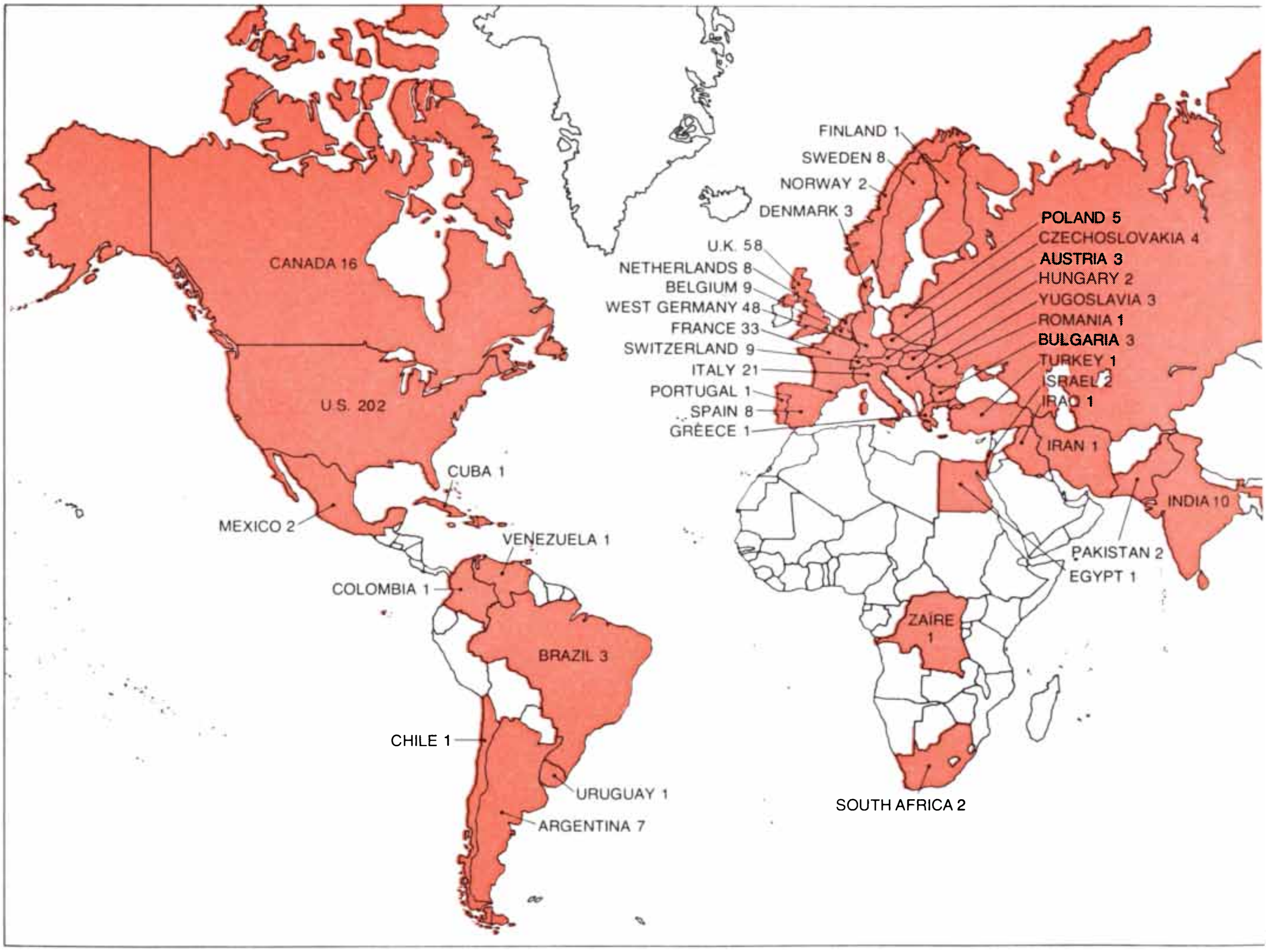
In addition the so-called security assurances to the non-nuclear-weapons states in the declarations of the nuclear-weapons states in the Security Council in June, 1968, had lost what little meaning they had ever had. With China having the power of veto, action by the Security Council to implement the assurances seemed at best doubtful.

Under the circumstances it was not surprising that even before the Indian nuclear explosion the Nonproliferation Treaty had lost a great deal of its force. The pent-up frustrations of a number of non-nuclear-weapons powers may have found a psychological release in India's having breached the walls of the exclusive big-power club.

The Indian explosion also came at a time when there had been a sudden upsurge of interest in nuclear power as a source of energy. The energy crisis and the quadrupling of the price of oil have stimulated the search for alternative sources of energy and have made nuclear power much more economically attractive than it was before. There now appears to be a kind of commercial competition among a number of countries in the Western world to sell reactors, fissionable material and nuclear equipment. Sales to Argentina, Egypt, India, Indonesia, Iran, Israel and South Korea are merely the most publicized ones.

It may take a year or two for another country to explode a nuclear device, and several years for some of the other potential nuclear powers to do so, but there are about a dozen countries that can, if they choose, go nuclear over the next five years, and another dozen can do so over the following five years. Although few of these countries have their own chemical-separation plants for reprocessing the spent fuel from reactors into fissionable plutonium, such plants can be built without much difficulty. It has been estimated that a reprocessing plant capable of producing enough plutonium for two or three explosive devices a year could be built in a year by any reasonably advanced country at a cost of a few million dollars. Even if the cost has been grossly underestimated, it is clear that the amount of money involved is not large. Moreover, a French company stands ready to sell complete plutonium-reprocessing plants.

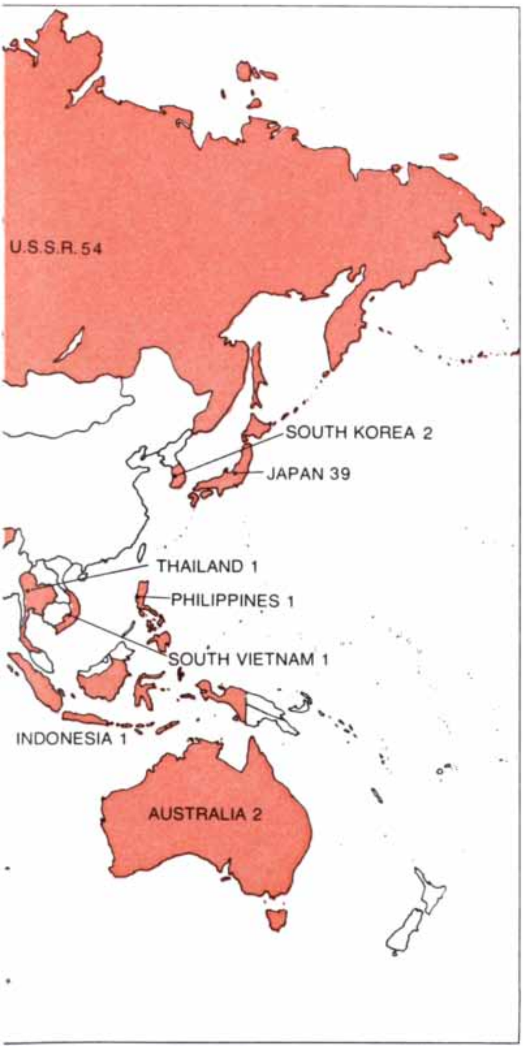
There would seem to be a kind of "domino theory" that is more applicable to countries going nuclear than to countries falling prey to a foreign ideology. Whether it is regarded as the *n*th-country problem or as a kind of chain reaction, each time a country goes nuclear it increases the incentives or pressures for its neighbors and other similarly situated countries to do so. Few doubted that once the U.S.S.R. had joined the U.S. as a member of the nuclear club all the other great powers would follow suit. As long as there was a "firebreak" between the big powers, which are permanent members of the Security




**NUCLEAR REACTORS currently in operation or under construction in 48 of the 106 member states of the International Atomic Energy Agency (IAEA) are indicated on this world map. The numbers shown include both power reactors and research reactors; they are derived from the 1974 edition of *Power and Research Reactors in Member States*, published by the IAEA. In principle weapons-grade material (either plutonium or uranium) can be diverted from the fuel cycle of any fission reactor. The Nonproliferation Treaty provides that the parties agree to accept the safeguard procedures set up by the IAEA to prevent the "diversion of**

Council, and all other powers there was a chance of holding the line against the further horizontal proliferation of nuclear weapons. Once a middle-sized or smaller power joins the nuclear club, however, there is little reason for other middle-sized or smaller powers to refrain from joining.

The countries that have not signed the Nonproliferation Treaty are the most likely candidates to go nuclear. They refrained from signing the treaty precisely because for one reason or another they wanted to keep their options open. The fact that India has now dared to go nuclear, with overwhelming domestic approval and comparatively little international criticism, may well encourage other countries to do so, or at the very least weaken those elements in such countries




**nuclear energy from peaceful uses to nuclear weapons or other explosive devices." The IAEA safeguards apply to all fissionable materials and all peaceful nuclear activities. China does not participate in the IAEA.**

that oppose their going nuclear. The delays in ratification by countries that have signed the treaty but have not yet become parties to it is an indication of their desire to move slowly in this field. Each of these countries has its eye on the others, and what any one will do may depend on what others do. No country wants to be placed in a position of perceived inferiority to others. If one other country should go nuclear, it would be difficult to keep the dam from bursting. Even those countries that had ratified the Nonproliferation Treaty could withdraw on three months' notice. As one country after another went nuclear, it would not take long for some parties to give notice of their withdrawal. That would mark the inglorious end of the attempt to prevent the spread of nuclear weapons.

If this rather gloomy scenario is acted out, the prospect for world survival itself becomes rather gloomy. A serious problem arises from the fact that at least some of the new nuclear powers may not have the resources or the time to build sophisticated second-strike deterrent forces. They may opt for a small nuclear striking force that would provide them with local military superiority or with a deterrent against attack by a neighbor. The ultimate result will probably reduce rather than increase their security, as may well turn out to be the case with India if Pakistan, Indonesia or Iran should go nuclear.

The danger is that a small or middle-sized nuclear power involved in an acute crisis might fear that a nuclear neighbor might launch a first strike against it and in order to prevent such an attack might decide to launch a preemptive strike. Since the advantage would lie with whichever country struck first, that would create almost intolerable pressures to be the first to take action and could set off a nuclear war no one wants. Apart from the danger of the outbreak of such nuclear war by design, there is the more likely possibility of its happening as the result of accident, miscalculation, misinterpretation of orders, blackmail or sheer madness.

There are real dangers of such an "accidental" war even between the great nuclear powers, but the dangers are becoming less because of "hot line" communication links, better command and control, and the evolution of détente. In a world of nuclear first-strike powers the dangers become infinitely greater. If one could work out all the permutations and combinations of the possible ways in which such a war could begin, the probability of its beginning sooner or later would become almost a certainty. That a local or regional war could take place without involving the great nuclear powers is quite doubtful.

Prime Minister Gandhi has assured Pakistan and the world of "the peaceful nature and the economic purposes of this experiment" and has stated that "India is willing to share her nuclear technology with Pakistan in the same way that she is willing to share it with other countries, provided proper conditions for understanding and trust are created." One can only speculate whether or not such sharing would extend to the design of nuclear explosive devices either by agreement with Pakistan or by participation in a regional or a global international regime for the conduct of peaceful nuclear explosions under safeguarded conditions.

If India is sincere in its intention to use nuclear explosive devices solely for nonmilitary purposes, it should be prepared to convert this unilateral statement of intention into a binding legal commitment by treaty or otherwise on a bilateral, regional or global basis. It is likely that India would insist that any commitment it undertakes be universal and not selective or discriminatory.

One can certainly conceive of an international regime for the conduct of nonmilitary nuclear explosions, whereby all parties, including nuclear-weapons powers, would agree not to conduct such explosions themselves; they would instead be undertaken either by some international authority composed of nuclear powers or by some designated nuclear powers, and only after the project in question had been examined and approved by some international body. The parties would all have to pledge never to use such explosives for military purposes. It might well be in the interest of all the nuclear powers to agree to undertake any approved project free of charge; the costs are in any event quite small (from $150,000 to $600,000 per explosion). If they were free, it might provide some inducement to underdeveloped countries not to seek to acquire their own capability.

The Nonproliferation Treaty already commits the parties to create such an international regime and provides that the potential benefits of such explosives "will be made available to non-nuclear-weapons states party to the Treaty on a nondiscriminatory basis and that the charge to such parties for the explosive devices used will be as low as possible and exclude any charge for research and development." Because of opposition to the Nonproliferation Treaty, it might be better if the international regime were set up by the UN outside the framework of the treaty.

Although such an international regime would appear to be technically and legally feasible, it is far from clear that it would be politically acceptable either to the nuclear powers or to those nonnuclear states that might want to acquire their own explosive capability. Nevertheless, the idea is worth exploring.

An immediate step that might be undertaken would be to have a moratorium on all nonmilitary explosions by all powers, pending the examination of the idea of an international regime for such explosions. If the nuclear-weapons states would agree to such a moratorium, even if only for a fixed period of time, it might be possible to obtain the agreement of India and of all the other potential nu-

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# CANDIDATES FOR THE NUCLEAR CLUB

Of the countries that have not signed the Nonproliferation Treaty the most obvious candidate to join the second-rank club of nuclear powers is Pakistan, which has announced its intention to keep abreast of India. Pakistan, like India, has a nuclear power reactor supplied by Canada, fueled by enriched uranium. Unless Pakistan is helped by China or some other power, however, it may take several years before it acquires a plutonium-reprocessing plant and is ready to undertake testing. It is noteworthy that Pakistan is not a party to either the 1963 Partial Test-Ban Treaty or the Nonproliferation Treaty and therefore need have no legal inhibitions about testing in the atmosphere.

Argentina, like Pakistan, is not a party to the Partial Test-Ban Treaty or the Nonproliferation Treaty. In addition to having several nuclear reactors (under IAEA safeguards) Argentina is one of the few countries that have a plutonium-reprocessing plant. Thus Argentina is in a position to produce its own plutonium and to explode a nuclear device whenever it so decides. Argentina has also recently entered into a nuclear-cooperation agreement with India. If Argentina goes nuclear, Brazil, which has always upheld its right to conduct peaceful nuclear explosions and which regards itself as an emerging great power, will not be far behind. Chile also might decide that it too has to go nuclear.

South Africa, in addition to having several nuclear reactors (under IAEA safeguards), is one of the largest uranium-producing countries. Moreover, South Africa has announced that it has a new secret process for enriching uranium, in which case it can explode a uranium device without waiting to acquire a plutonium device. The vice-president of the South African Atomic Energy Board stated after the Indian explosion that South Africa has the capability of making a bomb and is more advanced in nuclear technology than India. He stressed that South Africa would use its available uranium and nuclear technology only for peaceful purposes (whatever that may now mean). Apart from military reasons, South Africa may have an additional incentive to go nuclear. If it has in fact invented a new process for enriching uranium, it will want to find markets for the sale of its enriched material. It has recently entered into an agreement providing for the sale of uranium to France, and it may want to explode a peaceful uranium device of its own to demonstrate the effectiveness of its enrichment process and the quality of its product.

Israel has repeatedly stated that it "will not be the first country to introduce nuclear weapons into the Middle East," a rather cryptic statement. Most experts believe that all that Israel needs to make an atomic bomb is to turn the last screw. The French-supplied reactor at Dimona, which is not subject to IAEA safeguards, has since 1964 had the capacity to produce enough plutonium to manufacture one bomb a year. It is not known, however, whether Israel has a plutonium-reprocessing plant. Although Israel does have a grave security problem, many observers believe that it has a tacit agreement with the U.S. not to go nuclear, in exchange for an American commitment to provide all the conventional armaments that Israel may need to defend itself against Arab attack. Nevertheless, it is generally believed that Israel may have several untested nuclear weapons that it might use in an extreme situation if the survival of its cities and people were in serious jeopardy. In December, 1974, President Katzir stated concerning nuclear weapons: "If we need them, we will have them." As long as the present uneasy truce continues, there is no reason for Israel to go nuclear, but if the negotiations should break down or an acute threat should suddenly arise, it is possible that Israel might wish to demonstrate its nuclear capability by exploding a nuclear device for peaceful purposes. The Indian test explosion will certainly make it easier for those in Israel who support such action to argue in favor of such a test.

Egypt has signed the Nonproliferation Treaty but has not ratified it and has announced that it will not do so unless Israel does. Egypt is far behind Israel in nuclear technology, and stories have circulated in the diplomatic world for some years that Egypt has asked India and other countries to help it acquire nuclear weapons or nuclear-weapons capability (without success). The agreement last June by President Nixon to provide two 600-megawatt nuclear power reactors, one to Egypt and one to Israel, has raised serious questions. Such a reactor could produce enough plutonium to make more than 10 medium-sized nuclear bombs a year. No matter what safeguards are written into the agreement, including placing the reactor under IAEA safeguards and returning the spent fuel to the U.S. for reprocessing, it is always possible for a country wanting to do so to evade its commitments or abrogate the agreement. In answer to those who oppose the supply or sale of nuclear reactors to Egypt and Israel, American officials say that if the U.S. does not go ahead, then France or some other country will do so and will probably not insist on safeguards as strict as those the U.S. would require. Because of Israel's opposition to placing all its fissionable material under international or American safeguards and inspection, the future of the agreement to supply reactors to Egypt and Israel is unclear. In any case Egypt is arranging to obtain a large power reactor from France.

Spain has not signed the Nonproliferation Treaty and has drawn attention to its discriminatory character and to Spain's security situation. Spain is the only large country in western Europe that is not a member of the North Atlantic Treaty Organization, although it does have various defense agreements with the U.S. It also has uranium re-clear powers while the question was being studied. India cannot be too comfortable at the thought of her neighbors going nuclear, and the other potential nuclear powers would have little to lose by agreeing to the delay. Once again, however, as in all nuclear matters, the nuclear-weapons states would have to lead the way. It would clearly be in their interest to do so.

During the moratorium, or independently of it, it might be useful if another international group of experts were convened by the UN to consider all aspects of nonmilitary nuclear explosives. It is becoming clear that such devices are unlikely to bring the benefits that were hoped for. The first underground explosion was not detonated until 1957, and it is barely a decade since the exploration of the practical possibilities was undertaken. Here again nothing would be lost by allowing a year's delay for a more thorough study of the entire question.

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sources, several nuclear reactors and a pilot plutonium-reprocessing plant, which would enable it to acquire a nuclear capability if it so chooses.

In the category of countries that have signed the Nonproliferation Treaty but not ratified it, the main countries are all potential nuclear powers. They include the technologically advanced Euratom countries: West Germany, Italy, the Netherlands and Belgium, all of which have several nuclear reactors. In addition there are plutonium-reprocessing plants in West Germany, Italy and Belgium. West Germany and the Netherlands are also partners with Great Britain in centrifuge plants for enriching uranium. West Germany is bound by a 1954 treaty not to manufacture nuclear weapons on its territory. All the Euratom countries have signed safeguard agreements with the IAEA, and West Germany, the Netherlands and Belgium have obtained approval from their parliaments to ratify the Nonproliferation Treaty. Italy, however, is reluctant to complete the process of ratification, and the entire matter is therefore in abeyance. Italy's reluctance seems to be linked to fears that other less advanced Mediterranean countries, such as Israel, Egypt or Spain, may go nuclear. It is questionable whether the other Euratom countries could or would go ahead with ratification without Italy. Switzerland, which is also advanced in nuclear technology, appears to be holding up its ratification of the treaty until the Euratom countries ratify it.

Japan not only has a highly developed nuclear technology but also has a plutonium-reprocessing plant. It can thus go nuclear whenever it chooses. Public opinion in Japan is overwhelmingly opposed to all forms of nuclear tests and weaponry, and Foreign Minister Toshio Kimura announced in September, 1974, at the UN General Assembly that Japan was preparing to ratify the Nonproliferation Treaty. Nevertheless, there is a small but growing tendency in Japan to delay ratification until the future of the Nonproliferation Treaty is clarified, and this tendency seems to have been strengthened by the Indian explosion. It is unlikely that Japan will deposit its instrument of ratification until it is satisfied that the Euratom countries will also do so. Rather surprisingly, some Chinese nuclear experts have privately urged Japan to go nuclear.

South Korea, although not as advanced technologically as Japan and the Euratom countries, does have two research reactors in operation and two power reactors under construction. Security problems are a major consideration for South Korea, but its ultimate decision whether or not to go nuclear will probably depend on what other countries do, particularly in that part of the world.

Indonesia also has a research reactor and appears to be in the process of acquiring some power reactors, which should not be difficult in the light of that nation's rapidly growing oil revenues. Following the Indian explosion there were public statements predicting that Indonesia would go nuclear or calling for it to go nuclear. It is not likely to do so, however, for several years.

Among the potential nuclear powers that are party to the Nonproliferation Treaty, Canada and Sweden are examples of countries that have had the capability for a number of years to go nuclear but have unilaterally decided that it is not in their interest to do so. Other countries with a highly developed nuclear technology are Taiwan, Australia and Norway, probably in that order. Taiwan also has a pilot plutonium-reprocessing plant and thus can quite easily exercise the nuclear option if it chooses, particularly if it regards its security as being in jeopardy. Iran, which now has a research reactor, is somewhat farther down the line, but it has recently embarked on a program to acquire 12 large power reactors and has entered into agreements with France, West Germany and the U.S. to obtain several power reactors. In addition Iran has an agreement with the U.S. whereby the U.S. will undertake enrichment work with Iranian uranium. Iran is also participating in the construction of a large uranium-enrichment plant in France. With its rapidly increasing wealth from oil, Iran can readily acquire a potential nuclear capability, and there are some elements in the country that are urging it to do so.

Apart from Israel, Egypt and Iran no other Middle East country has any potential nuclear capability at present. Nevertheless, the combination of the unstable political situation in that part of the world, the Arab-Israeli conflict and the vast wealth that is being accumulated by the oil-rich countries of the area would seem to make the Middle East an area of particular concern. There have already been press reports of countries in the region being interested in buying or otherwise acquiring nuclear weapons or nuclear-weapons capability. The Indian explosion will certainly not damp any such ideas; it might even tend to encourage them. Apart from action by governments of states in the region there is a growing danger that terrorists will try to steal a nuclear weapon or fissionable material for either blackmail or ransom. That danger will, of course, increase over the years as nuclear power reactors, fissionable materials and nuclear technology proliferate in the area and in the world at large. The world has not been conspicuously successful up to now in dealing with Arab hijacking and blackmail involving less dangerous weapons.

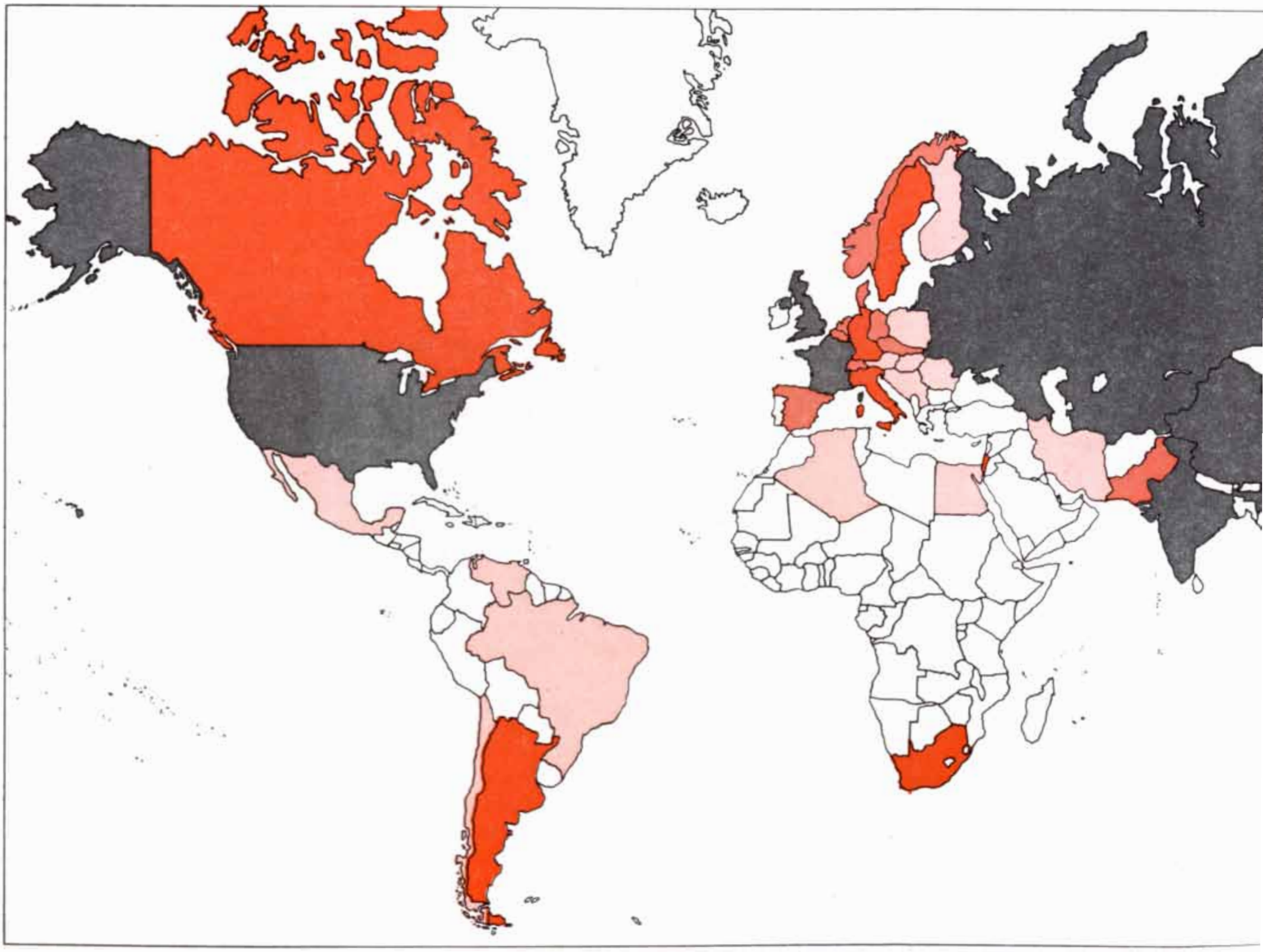
All the Warsaw Pact allies of the U.S.S.R. have been assisted by the Russians in the building of research reactors, and nearly all of them have power reactors in operation or under construction. East Germany and Czechoslovakia are the most advanced technologically. All of them are party to the Nonproliferation Treaty. It is clearly in the interest of the U.S.S.R. that none of them should acquire any nuclear explosive capability, and they are not likely to do so as long as the Nonproliferation Treaty remains an effective treaty and retains any legal or moral force.

Another idea that merits careful consideration is the possibility of establishing nuclear-free zones in different regions of the world. Among the lessons to be drawn from the creation of a nuclear-free zone in Latin America (by the Treaty of Tlatelolco, signed in 1967) is that the idea must have the sympathetic general support of all the important countries in the area. It is useless to think that a country can be maneuvered by political gamesmanship into agreeing to a treaty unless that country perceives the treaty as being in its own interest. It is also axiomatic that even if a country is a party to a treaty, it will not remain a party if it considers that events have caused the treaty to be contrary to its most important interests.

Finally, it has been suggested that the countries that export fissionable materials should form a "suppliers' club" and agree to supply nuclear materials and equipment only to those countries that would agree not to undertake nuclear explosions of any kind, to place all their nuclear facilities under IAEA safeguards and to return all spent fuel to the supplier countries for reprocessing. Such measures would, of course, be useful, but like any embargo they would be fully effective only if all supplier countries agreed to abide strictly by the rules.

In August, 1974, the U.S. joined other important supplier nations in a public undertaking contained in letters to the IAEA stating that it would not provide fissionable material or nuclear equipment to any non-nuclear-weapons state unless the material and equipment were subject to safeguards under an agreement with the IAEA. Some important supplier states, such as France and South Africa, have not, however, joined in the undertaking. Moreover, the agreement applies only to future supplies and does not affect previously supplied material. Even the regulations promulgated by Canada last December, which provide the strictest safeguards imposed by any supplier country, can be evaded by countries that build their own small reactors and plutonium-reprocessing plants, since most countries have at least low-grade uranium resources.

Unless the safeguards govern all nuclear activities (as is required by the Nonproliferation Treaty) and not merely current and future transfers of material and equipment, opportunities for evasion will remain. Moreover, it would seem to be highly discriminatory if any non-nuclear powers that are not party to the treaty could acquire nuclear materials, equipment or technology under less stringent conditions than parties to the treaty. In fact, if the non-nuclear powers that are not parties are subject to safeguards less strict than those required



**POTENTIAL FOR NUCLEAR PROLIFERATION is represented graphically on this world map. The six current members of the nuclear club are shown in gray. The eight near-nuclear countries (that is, those with the capability of making nuclear weapons in a comparatively short time, given the political decision to do so) are in the darkest color. The countries that would require a somewhat**

of the powers that are parties, that would provide an inducement to avoid becoming a party.

One would have thought that, given the prospect of the further proliferation of nuclear weapons, the nuclear powers, which have the most to lose, would be galvanized into some kind of action in an attempt to prevent the emergence of a world of nuclear powers, but such is not the case. There is no evidence that the nuclear powers have any understanding of the seriousness of the situation. If they do have any such understanding, they have shown no urgency in attempting to cope with the situation.

There have been three sessions during the past year of a preparatory committee for the holding of next month's review conference in Geneva. In the course of these preparations the nuclear-weapons powers have given no indication that they have learned any lessons from the Indian explosion or that they have any intention of abiding by their commitments under the treaty. They of course want to see as many nations as possible become parties to the Nonproliferation Treaty, and they have attempted to put pressure on the Euratom countries and Japan to ratify the treaty before the review conference. It seems that the only other measures contemplated by them are to tighten the safeguard provisions of the treaty in order to ensure that in the future no fissionable material can be diverted to nuclear explosions of any kind, whether peaceful or military, by a non-nuclear state.

These objectives are commendable in themselves, but they hardly approach the requirements of the situation in the world today. The situation is that more and more countries will go nuclear unless it can be clearly demonstrated to them that it is in their interest not to do so. Sanctions in the way of withholding nuclear assistance are hardly likely to be effective against the newly rich oil-exporting countries in a situation where the nuclear powers and other supplier states are competing to sell nuclear reactors, materials and equipment to them. Nor are they likely to be more effective against the poor countries that are determined to close the gap between themselves and the rich countries and that see nuclear technology as one of the ways of closing it. Countries that are determined to evade controls will find ways to evade them. With China encouraging them to be more activist, and with the example of India as evidence that the wishes of the big powers can be flouted with impunity, they may attempt to exploit their sheer numerical majorities to engage in confrontations with the rich countries in order to extract concessions from them.

The longer-term goal of the underdeveloped countries is to readjust the balance between themselves and the developed countries, which means a more equitable sharing of the world's wealth. A shorter-term goal is to acquire nuclear capability either as a step toward attaining their longer-term goal or as a means of their using nuclear threats or blackmail to achieve political and economic gains, somewhat in the way that the oil-producing countries have used oil as a weapon.

Both the longer-term and shorter-term goals are still distant. The immediate preoccupations of the non-nuclear countries are their security and their economic and political situation. A decisive role with respect to the future of the concept of nonproliferation of nuclear weapons will be played by a handful of near-nuclear powers that have not signed the Nonproliferation Treaty. Whether or not these countries proceed to exercise the nuclear option within the next few years will depend in large part on the international climate of opinion. The Indian test explosion has undoubtedly weakened the entire principle of nonproliferation, but the situation may not be entirely hopeless. Domestic considerations and a country's perception of its security requirements, its role and status in the world and its aspirations for future economic development through the application of nuclear energy (whether rightly or wrongly held) will determine whether or not it decides to go nuclear. A most important element in these considerations will be the actions of the great powers, in particular the two superpowers. The standard of international behavior they set, particularly in the field of nuclear-arms control, is bound to have a great and perhaps decisive influence on the actions of the non-nuclear powers. The two superpowers must take the lead. They are the ones that must replace the ethic of the arms race by the ethic of arms control.

The U.S. and the U.S.S.R. must accept the burden of changing the world attitude toward nuclear weapons. Only they can halt and reverse the vertical proliferation of nuclear weapons, which is a necessary condition to preventing their horizontal proliferation. If they continue to militarize the world with both nuclear and conventional weapons, they can hardly expect that other countries will refrain from acquiring such weapons. They have the responsibility of establishing the illegitimacy of the nuclear-arms race and the legitimacy of nuclear restraint and arms control.

If it becomes clear at next month's review conference that the nuclear-weapons states are prepared to live up to the obligations they undertook in the Nonproliferation Treaty, then there is a chance that the treaty can be strengthened and reviewed. This is probably the last chance for the prevention of an uncontrolled nuclear-arms race. There is no guarantee, even if the nuclear-weapons states avail themselves of this last chance, that they would be successful in halting the trend toward proliferation. If they do not make a credible attempt to do so now, however, it would seem to be inevitable that other non-nuclear countries will follow the lead of India. We shall then all have to learn to live as best we can in a world full of nuclear powers.

**longer time to acquire a nuclear-weapons capability are represented in lighter shades of color: the lighter, the longer the time.**

# Experiments in the Visual Perception of Texture

*The discovery of textures that are indistinguishable even though their constituent elements are different suggests how the visual system organizes patterns into the percepts "figure" and "ground"*

by Bela Julesz

When we are confronted with a device or a system whose workings we do not understand, the first question we usually ask is: What can it do? One often finds that having detailed information about the internal structure of the device or system does not help much in establishing its capabilities. When we are confronted with an ultracomplex system, such as the human brain or a large computer, it is sometimes more pertinent to ask: What can it not do? Indeed, one of the profound mathematical insights of this century is the discovery by Alonzo Church and others that there are important mathematical problems that cannot be solved by a class of computers that had been thought to be very powerful, the class of hypothetical mechanisms known as Turing machines.

I shall not dwell here on the controversial question of whether the human brain is more powerful than a Turing machine. What I shall take up is certain limitations that seem to be inherent in the human visual system, a part of the most complex system yet known in the universe. My colleagues and I at the Bell Laboratories have spent much time trying to find perceptual tasks that are beyond the visual system's processing capabilities. In order to clarify the role the visual system plays in perception we have tried to confine our studies to tasks involving pure perception, that is, tasks that can be performed spontaneously and do not require help from cognitive processing stages of the brain that involve scrutiny. My distinction between pure perception and cognition is best illustrated by a few examples.

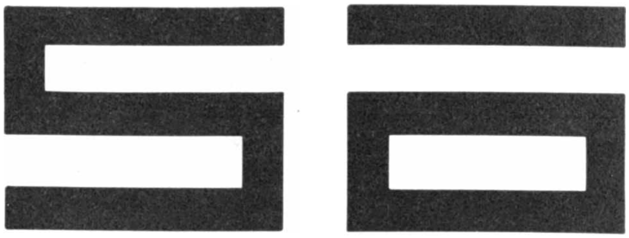
The first example was devised a few years ago by Marvin L. Minsky and Seymour A. Papert of the Massachusetts Institute of Technology. It consists of two spiral patterns that appear to be similar to each other [*see illustration at left at top of opposite page*]. Actually one of the patterns is drawn with a continuous line and the other is not. This fact cannot be perceived spontaneously. You have to trace the lines point by point with your finger (or perhaps by slow scanning eye movements) to convince yourself that one pattern is formed by an unbroken line and the other is not. Any visual task that cannot be performed spontaneously, without effort or deliberation, can be regarded as a cognitive task rather than a perceptual one. It is evident that one could simplify the Minsky-Papert spiral patterns to the point where their connectedness or lack of it would be instantly apparent [*see illustration at right at top of opposite page*].

The second example demonstrates even better what we mean by pure perception. The illustration at the bottom of the opposite page shows three squares containing patterns of black and white cells. In the square at the left the cells are completely random. The square in the middle also seems to contain a random array. On closer scrutiny, however, one can see that it consists of four quadrants, all identical. If we now take the same four quadrants and mirror them across the horizontal and vertical axis, we obtain the pattern at the right, in which the twofold symmetry can be perceived without effort. In this example the redundancy of the four repeated quadrants and of the mirrored quadrants is the same, yet symmetry is perceived and repetition is not. The scrutiny needed for the latter again requires some cognitive processes, which we want to exclude.

These examples were not meant to show the limitations of visual perception but rather to illustrate the difference between effortless perception and some other processes that require scrutiny. To clarify further, one should not conclude that the mere presence of randomness in an array presents a barrier to the perception of periodicity. Thus if the periodic distance is sufficiently reduced, the periodicity of random arrays can be perceived immediately [*see top illustration on page 36*]. This even suggests that perception of symmetry does not depend on the entire pattern, only on the presence or absence of symmetrical pairs of cells near the symmetry axis. Indeed, if one takes an array of black and white cells with twofold symmetry and inserts a stripe of random black cells eight cells wide across the horizontal and vertical axes of symmetry, the overall symmetry of the array is largely if not totally destroyed [*see top square in bottom illustration on page 36*]. Conversely, if one inserts two symmetrical stripes eight cells wide in the same position in an otherwise random array, the overall array appears to be surprisingly symmetrical [*see bottom square in bottom illustration on page 36*].

These demonstrations clearly illustrate a basic limitation of the human perceptual system. It can perform certain kinds of perceptual task well until the system is overloaded in some way. There are, of course, many limitations of no particular interest. One can imagine many properties of images that were irrelevant to survival during animal evo-

**LIMITATIONS OF PURE PERCEPTION are demonstrated in these two figures devised by Marvin L. Minsky and Seymour A. Papert of the Massachusetts Institute of Technology. It is not spontaneously apparent that the figure at left consists of one continuous line and that figure at right has two discontinuous elements.**



**EXAMPLE OF PURE PERCEPTION, requiring no assistance from cognitive processes, is demonstrated by these figures in which the connectedness or lack of it is instantly apparent. Limitations of pure perception in perceiving connectedness of more complex patterns result from gradual overloading of perceptual system.**

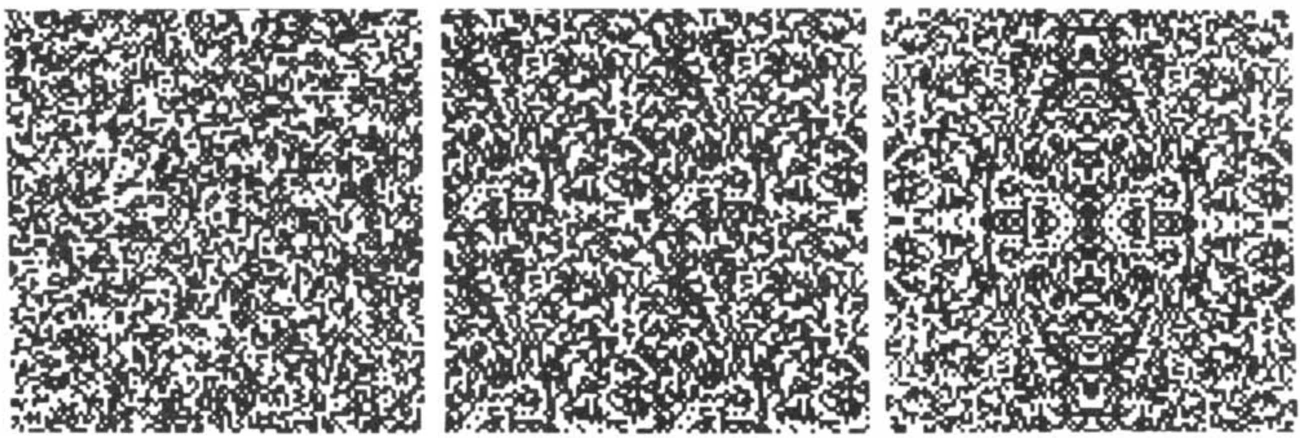
lution; accordingly the perceptual machinery provides no means for their extraction. Hence when a certain image property cannot be perceived, it implies either that perception of the property was not crucial for the survival of our remote ancestors or that the extraction of the property exceeds the processing power of the perceptual system.

Let us therefore examine more closely the phenomenon of visual texture discrimination, a task with obvious survival value, and see what we can learn by manipulating the complexity of the textures. We shall see that texture discrimination ceases rather abruptly when the order of complexity exceeds a surprisingly low value. Whereas textures that differ in their first- and second-order statistics can be discriminated from each other, those that differ in their third- or higher-order statistics usually cannot. In due course I shall explain more precisely what is meant by order of statistics; for the moment, speaking roughly, it is like describing a structure or a phenomenon by increasing the number of variables (degrees of freedom or number of dimensions).

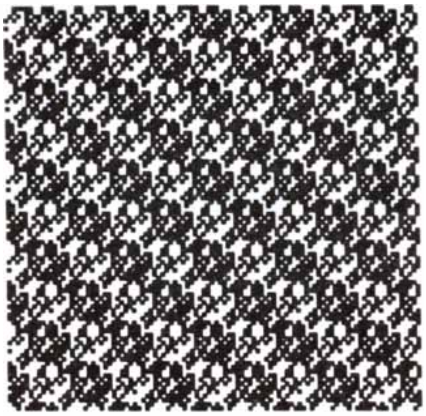
Each new variable gives a more detailed description of the structure, but the number of parameters increases exponentially with the number of variables. As a result the jump from a second-order statistical description to a third-order one brings with it a vast increase in computational requirements that seems to surpass the capabilities of the perceptual system. Thus we encounter a case where the visual system is genetically programmed for texture discrimination (think of the importance of penetrating animal camouflage) but cannot cope with structures beyond a certain complexity.

One might regard this overloading of the visual system as being analogous to what happens when the system is unable to perceive periodicity or connectedness, as in the examples given above. In the perception of periodicity or connectedness, however, the overloading of the system occurs gradually as the periodicity distance or complexity is increased. Any number of models can be proposed to explain such a gradual decrease in performance. The abrupt decrease in performance that occurs in texture discrimination is quite another matter, suggesting a clear structural constraint on the interconnecting neural network of the perceptual machinery.

My interest in texture discrimination dates back to 1962, when I first used a computer to generate pairs of textures, presented side by side, and studied the conditions under which they could or could not be discriminated. I found that for a limited class of textures generated by Markov processes the texture pairs could not be discriminated if they agreed in their second-order statistics. In a Markov process the content of each unit cell in a linear sequence—that is, whether a cell is to be black, white or some intermediate shade of gray—is determined by the content of some number of preceding cells according to a prescribed mathematical formula. I should



**PERIODIC AND SYMMETRICAL ARRAYS provide further examples of the difference between pure perception and processes requiring cognitive effort. The computer-generated array at the left is random. The array in the middle may appear equally random, but on closer inspection one can see that it consists of four identical quadrants. If one of the quadrants is now mirrored across the vertical midline, and result is mirrored again across horizontal midline (*right*), the twofold symmetry of final array is apparent.**



**PERIODICITY** of random-array figures can be perceived without special effort if the distance of the periodicity is not too large.

**PERCEPTION OF SYMMETRY** seems to require the presence of symmetrical pairs of cells near the symmetrical axis only. Thus the twofold symmetry in the image at the top is largely destroyed by the insertion of random black cells in two stripes eight cells wide (*marked by faint color*) across horizontal and vertical axes of symmetry. On the other hand, insertion of symmetrical stripes eight cells wide in same location in an otherwise random array (*bottom*) creates impression the entire image has twofold symmetry.

also explain that if two textures are the same in their second-, third- or $n$th-order statistics, they are necessarily the same in all statistics of lower order, that is, in their first-, second- and $(n - 1)$th-order statistics, since from statistics of a given order statistics of any lower order can be uniquely determined.

Because of certain limitations in these first experiments with computer-generated textures it was highly questionable whether one could make a "mathematical," or quantitative, conjecture about the limits of human texture perception, for example by stating in general that "no texture pairs can be discriminated if they agree in their second-order statistics." Indeed, 10 years ago, when I reviewed some of my earlier findings in these pages, I was skeptical of statistical considerations in texture discrimination because I did not see how clusters of similar adjacent dots, which are basic for texture perception, could be controlled and analyzed by known statistical methods [see "Texture and Visual Perception," by Bela Julesz; SCIENTIFIC AMERICAN, February, 1965].

In the intervening decade much work went into finding statistical methods that would influence cluster formation in desirable ways. The investigation led to some mathematical insights and to the generation of some interesting textures. What is more, the conjecture that "no texture pairs can be discriminated if they agree in their second-order statistics" seems to hold for a surprisingly large class of textures. Although a few rather weak counterexamples have been found, the conjecture can still be maintained with only minor modifications. Only time will tell if stronger counterexamples exist. In any event the new textures that have come out of the work of the past decade are so striking and so contrary to expectation that I think the texture-discrimination problem is worth revisiting.

Let me begin by defining what I mean by texture discrimination. If you look at the top illustration on the opposite page, you will see two square arrays of black dots, with each dot containing a white *U*. Moreover, each array contains a region of one texture embedded in a region of a different texture. In the array at the left the regions containing the two dissimilar textures can be perceived at a glance. In the array at the right, however, the areas defined by the two textures are not immediately evident. Only after close scrutiny is one able to detect that the *U*'s are upside down in one quadrant of the entire array. Such an array will be regarded as a nondiscriminable texture pair.

Although the distinction between discrimination and nondiscrimination is self-evident, it can be precisely quantified. One can present patterns such as those just described in a brief flash and ask a subject whether or not he saw a square area different from the rest and which quadrant it was in. The strength of discrimination can be measured by the duration of the presentation and the number of errors in identification of the quadrants.

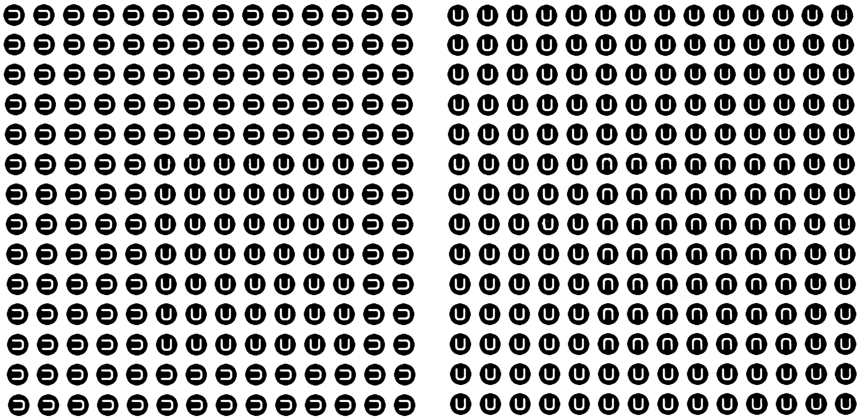
The next question is how to specify textures. In the case of the random textures that we usually employ we can describe the textures by their statistics of different order. The first-order statistics have to do with brightness, or, to be precise, luminance: the frequency that any given point of the texture will have a certain luminance. For example, one texture might have first-order statistics indicating that it is composed of dots of only three luminances: black, white and gray, each occurring with a probability of one-third. Another texture might be made up of dots of the same three luminances, but the black dots might occur with a probability of .5 whereas the gray and white dots each occur with a probability of .25. The second texture can easily be discriminated from the first texture because the second will appear much darker.

Let us now consider textures that share the same first-order statistics but differ in the second order. Such a texture pair is shown in the middle illustration on the opposite page. Both the left field and the right field contain an equal number of black dots placed at random, hence the overall luminance of the two fields is the same. In the right field, however, no two dots were allowed to fall within 10 dot diameters of any other dot, whereas in the left field there is no such restriction. Clearly the first-order statistics, that is, the $f_0$ ratio of black to white dots, are the same for both textures, but their second-order statistics differ. The difference can be demonstrated and quantified by dropping a dipole $r$ (such as a needle) on the two textures and observing the frequency with which both ends of the dipole land on black dots. The probability, $f(r)$, of this happening on the two different textures would be quite different and would provide a measure of the difference in the second-order statistics of the two textures. When one looks at the two textures, one sees instantly that they have a different granularity.

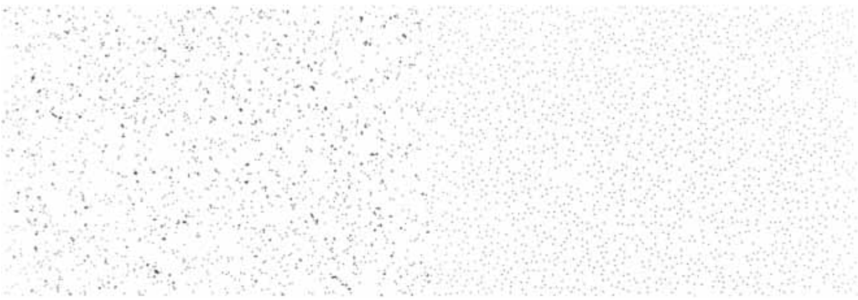
In 1962 I asked what would happen if textures had identical first- and second-order statistics but different third- or higher-order statistics. Could the textures be discriminated or not? One way to describe third-order statistics is to throw a triangle on a texture and note the probabilities with which its three vertexes land on dots of certain luminances.

In 1962, after I drew attention to this problem, two mathematicians, Murray Rosenblatt of the University of California at San Diego and David Slepian of the Bell Laboratories, invented a class of Markov processes that have identical first-, second- and $n$th-order statistics but that differ in their $(n + 1)$th-order. When I used these Markov processes to generate pairs of textures with identical first- and second-order statistics but different third-order statistics, I found they could not be discriminated from each other [*see left half of bottom illustration on this page*]. When a difference occurs in the second-order statistics, however, the difference is immediately seen as a difference in granularity [*see right half of illustration*].

Since Markov processes are inherently one-dimensional, they can be generated by scanning an image from left to right row by row, in the same way that a television image is scanned. Each texture point depends on the luminance of the preceding two points on the left; the resulting trigrams have different probabilities in the two textures, yet the textures cannot be discriminated from each other. The finding that the visual system cannot keep track of the presence or absence of the luminance combinations of three adjacent dots was rather unexpected. It is true that these Markov processes must have at least three luminance values (black, white and gray); thus the number of possible trigrams is 27. With four luminance values (black, two shades of gray and white) the number of trigrams jumps to 64. These are nevertheless low numbers. Furthermore, to simplify the discrimination task we selected texture pairs from the 64 trigrams such that, for example, one texture contained 32 trigrams and the other contained the remaining 32. (In other words, the two textures did not contain any trigrams in common.) With Newman Guttman, I tried the same Markov processes with musical "textures" and found that random melodies could be perceived as being different only if they possessed different second-order statistics; if the first- and second-order statis-

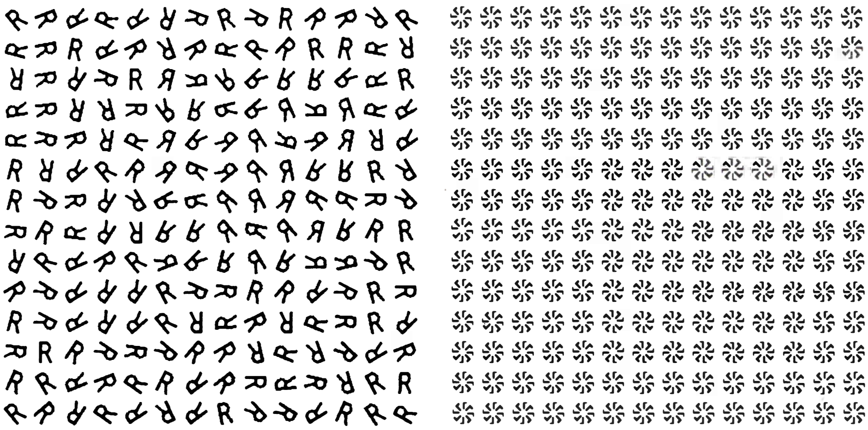


**VISUAL TEXTURE DISCRIMINATION** is studied by the author by flashing on a screen images with controlled statistical properties such as these and asking the subject if he can see an area of one texture embedded in an area of similar but different texture. In the image at the left the two textures have identical first-order statistics but different second-order statistics; the difference in textures can be perceived without effort. In the image at the right the two textures have identical second-order statistics in addition to identical first-order statistics. Here discriminating between the two textures requires deliberate effort.



**DIFFERENCE IN SECOND-ORDER STATISTICS**, which is readily visible here, is exemplified by these two textures, which have identical first-order statistics. The first-order statistics of the textures are identical because each texture consists of the same number of black dots; hence there is the same probability in both textures that a given point will have same luminance. In the left field the dots fall at random. In the right field, however, there are at least 10 dot diameters between dots. Thus if a dipole such as a needle were dropped on the two fields, the probability of both ends' touching a dot would be different in the two cases. Difference in probabilities signifies a difference in second-order (dipole) statistics.

**DIFFERENCE IN THIRD-ORDER STATISTICS**, which eludes spontaneous detection, is demonstrated in the image at the left. The left and right half-fields in that image have textures that are generated by a Markov process so as to have identical first-order and second-order statistics but to have different third-order statistics based on the sequential arrangement of cells of four different luminance levels: black, dark gray, light gray and white. Only by careful inspection can one see that the left half-field contains a few horizontal stripes of uniform luminance that are formed by three adjacent cells whereas the right half-field contains practically no stripes. In comparison the two textures in the image at the right can instantly be discriminated because they have different second-order statistics, which appear as a difference in granularity. In both textures cells of three luminance levels (black, gray and white) occur with equal probability; hence first-order statistics are the same. In the texture that largely fills the left side adjacent cells are statistically independent of one another in luminance whereas in the surrounding texture adjacent cells are related mathematically by a Markov process. This gives rise to different second-order statistics.



**NONDISCRIMINABLE TEXTURE PAIRS are produced when the textures have identical second-order statistics, as is demonstrated by these two examples. In each case a square area of one texture is embedded in a large square of different but closely similar texture. In the example at the left texture *A* in the large square is composed of identical micropatterns consisting of *R*'s in random orientations whereas texture *B* in the small square consists of mirror-image *R*'s. In the example at the right the two textures are made up of octopus-shaped micropatterns. The arms bend clockwise in texture *A* and counterclockwise in texture *B*. In both of the displays the second-order as well as the first-order statistics are the same. How identity of statistics can be simply demonstrated is explained in text of article.**

**LOCATION OF TEXTURE *B* in the texture pairs presented in the illustration above this one is indicated by light blocks of color. Color is not used, of course, when the texture pairs are flashed on the screen before an observer in actual studies of perceptual mechanism.**

tics were the same, the ear (like the eye) could detect no difference.

Unfortunately Markov processes are inherently one-dimensional, whereas vision is two-dimensional. Therefore I was not convinced of the general validity of the results obtained with the linearly generated Markov textures. A ubiquitous characteristic of naturally occurring textures is the presence of clusters of various sizes and shapes. Most of these two-dimensional clusters cannot be generated by one-dimensional Markov processes, and the few clusters that form by chance depend on the scanning rules in arbitrary ways. Obviously the clusters that do form are very different, depending, for example, on whether the dots are scanned line by line or generated along a spiral path starting in the center of the display. It is well known from neurophysiological studies that the visual systems of cats and monkeys incorporate cluster detectors in several stages of hierarchically increasing complexity, beginning at the retina of the eye and extending to the highest levels of the cerebral cortex.

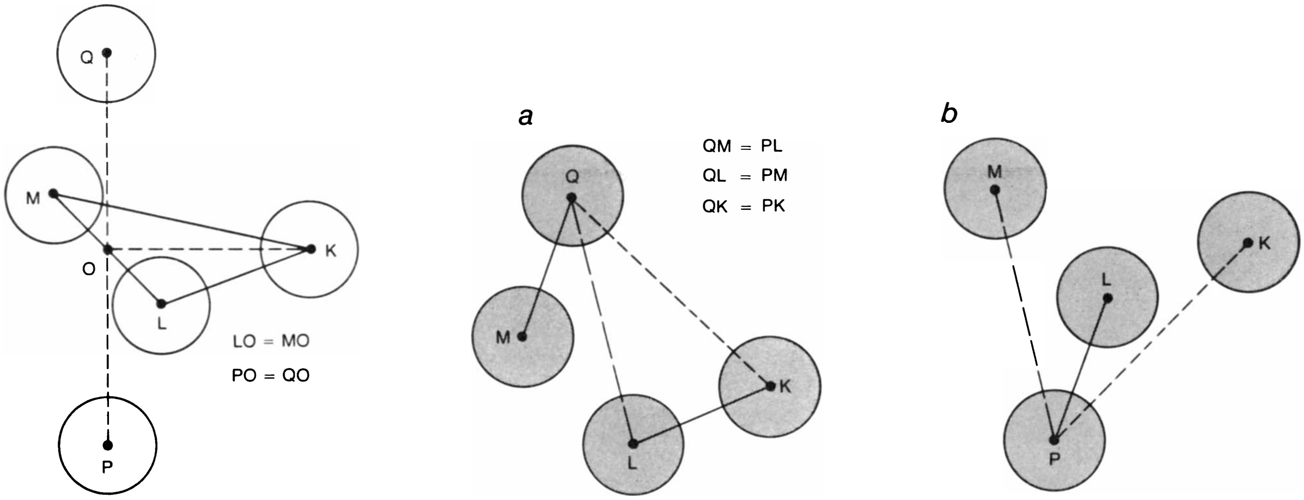
Typically these cluster detectors, or feature extractors, are neurons that fire only if in a local retinal domain to which they are connected (their "receptive field") certain features are present. The simplest of these receptive fields are concentric, with an excitatory center and an inhibitory surround (or vice versa), and they connect to neurons in the retina and in the lateral geniculate nucleus, a major switching center on the pathway to the visual region of the cortex. The simplest feature extractors in the visual cortex have similar antagonistically organized receptive fields, but their shapes are narrow ellipses. Both types of feature extractor ignore uniform illumination but fire for clusters whose shapes optimally match those of the receptive field. As a result they detect dots and line segments of particular diameters, widths and orientations. Some of the complex and hypercomplex feature extractors in higher cortical areas detect a hierarchy of increasingly complex stimulus features, which together make possible the remarkable feats of form recognition.

In view of these neurophysiological findings it seemed important to find ways to generate textures by some non-Markovian process that would incorporate clusters of desired shapes in a statistically describable manner. Therefore we looked for ways to generate two-dimensional textures of black and white dots (omitting shades of gray) in which the area fractions of black to white $f_0$ would be identical (thus providing identical first-order statistics) and in which the $f(r)$ dipole (or second-order) statistics would also be identical, but in which the third- or higher-order statistics would be different. Such two-dimensional textures would enable us to study the role of clusters in texture discrimination and to test the conjecture under the most general conditions in which such texture pairs cannot be discriminated.

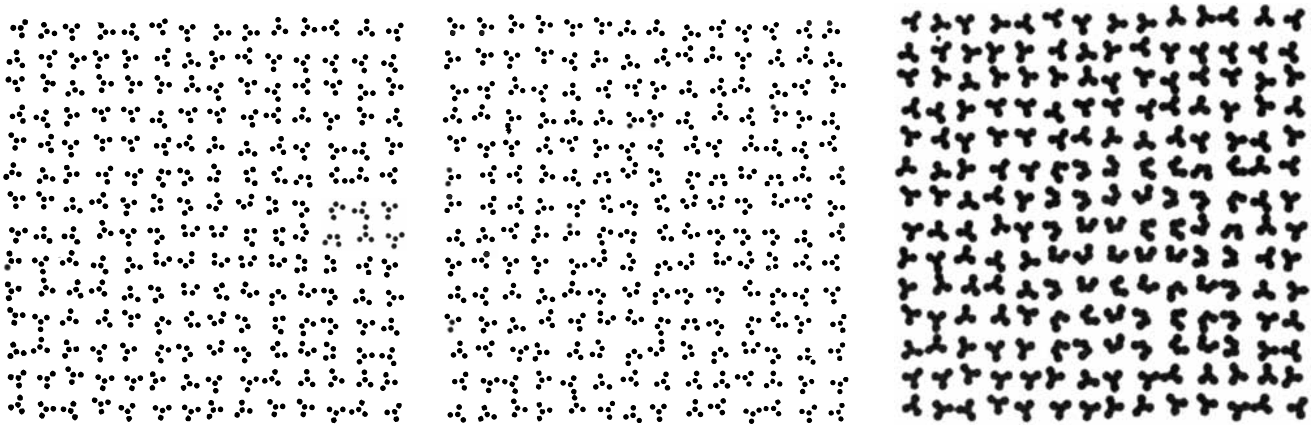
Only recently, with the help of two other Bell Laboratories mathematicians, Edgar N. Gilbert and Lawrence A. Shepp, and a physical chemist, H. L. Frisch of the State University of New York at Albany, were we able to find ways to generate the desired two-dimensional textures. As a matter of fact, we now have three different methods that generate the pairs of textures desired. Throughout our investigations we tried to generate texture pairs that would disprove the conjecture. To our mounting surprise many trivial counterexamples that we thought would certainly disprove the conjecture failed, and micropatterns that individually appeared very different yielded textures that could not be discriminated. Finally we did find a few subtle cases that could be regarded as counterexamples. As we shall see, however, a slight modification of the conjecture explains even these cases. In the rest of this discussion I want to share with the reader the thrill of this quest and the unexpected demonstrations that resulted from our efforts.

All our methods use texture pairs composed of identical micropatterns, either regularly spaced or thrown at random, with or without rotation, except that the micropattern *b* in texture *B* is derived from micropattern *a* in texture *A* by some rule. The procedure involved can be clarified by returning to the top illustration on page 37. On the left are two textures, *A* and *B*, derived by repeating the micropatterns *a* and *b* with a regular spacing, where *b* is derived from *a* by a rotation of 90 degrees. Obviously the second-order statistics for textures *A* and *B* must be different, because if one were to scatter needles (as dipoles) over the two textures, one would find needles on texture *A* whose end points fall on the *U*-shaped micropatterns in orientations that cannot be reproduced on the micropatterns of texture *B*, or if they can be reproduced, they can occur only with a different frequency. Because of this demonstrable difference in second-order statistics the left image is strongly discriminable in texture.

Now consider the image at the right in the same illustration. Here texture *B* embedded in texture *A* defies instant discrimination, evidently because micropat-




**METHOD OF GENERATING MICROPATTERNS** that yield texture pairs with identical second-order statistics begins with the construction of a triangle of arbitrary dimensions, *KLM*. At the midpoint of one side, say *LM*, a line is drawn perpendicular to *OK*, and on it points *P* and *Q* are placed so that *PO* equals *QO*. Five nonoverlapping disks are drawn with centers at *K*, *L*, *M*, *P* and *Q*. The three central disks and disk *Q* form the micropattern *a*; the same central disks and disk *P* form the micropattern *b*. The micropatterns have identical second-order statistics because any dipole whose ends touch any two disks in micropattern *a* can be matched by a dipole of equal length touching two disks in micropattern *b*. If micropatterns are also randomly rotated, a dipole of given orientation will touch pairs of disks with equal frequency in each micropattern. The micropatterns differ in third-order statistics, however, because a triangle, for example *KLQ*, can be placed on micropattern *a* in a manner that cannot be duplicated on *b*.



**ONLY WEAKLY DISCRIMINABLE TEXTURE PAIRS** are generated from the micropatterns *a* and *b* that are described in the illustration above this one, even though *a* and *b* in isolation appear very different. In each of the three displays a square of texture *B*, consisting of *b* micropatterns, is embedded in a large square of texture *A*, consisting of *a* micropatterns. In the display at the left the micropatterns are randomly rotated on evenly spaced centers. In the display in the middle the micropatterns are randomly thrown without overlapping, yielding texture pairs that are even harder to discriminate than the ones in the first example. In the display at the right the micropatterns are arranged exactly as in the first example except that now micropatterns have been fused by throwing them out of focus. Since second-order statistics are made different by this process, texture discrimination is enhanced.

tern *b* in texture *B* is derived by rotating micropattern *a* 180 degrees, with the result that textures *A* and *B* have the same second-order statistics in addition to the same first-order statistics. This can easily be verified by scattering dots and needles on texture *A* alone and placing the result on a table between two subjects who are facing each other. To one subject the *U*'s look right side up; to the other they look upside down. Yet both see the same probing dots and needles (only the end points of the needles interchange) touching the same parts of the same micropatterns. If, however, the demonstration is repeated to test third-order statistics by using triangles instead of needles, the statistics turn out to be different because a triangle of a given orientation (unlike a dipole, whose two ends are considered interchangeable) can be placed on a right-side-up *U* in a way it cannot be placed on an upside-down *U*.

A second method of generating texture pairs that contain clusters and identical second-order statistics involves using the mirror image of micropattern *a* of texture *A* to produce micropattern *b* of texture *B*. Here the micropatterns are allowed to rotate in random orientations. The verification that the two textures, *A* and *B*, have identical first- and second-order statistics but different third- and higher-order statistics is similar to the preceding verification except that now one observer views texture *A* in a normal manner and the second observer views the texture from behind, as if the plane on which the micropatterns *a* were thrown were transparent. It is clear that the first-order (single point) statistics and the second-order (dipole) statistics (because of random rotation) will be the same for both observers but in general will not be the same when the probing points are the corners of triangles or of polygons with more than three sides. (The special case of symmetrical triangles and symmetrical polygons must be excluded in such analyses.)

The left half of the upper illustration on page 38 is an example of textures composed of micropatterns that are mirror images of each other. The micropattern of texture *A* is the letter *R;* the micropattern of texture *B* is the mirror image of the same *R*. Both *R*'s are thrown in all possible orientations. It is impossible to discriminate the two textures. As a further experiment we designed an abstract micropattern, an octopuslike structure that is invariant under rotations that are multiples of 45 degrees. Micropatterns consisting of this structure and its mirror image provide the two textures shown in the right half of the upper illustration on page 38. Inspection of this image will reveal that in it texture discrimination is exceedingly difficult, if not impossible.

The third method of generating texture pairs that have identical second-order but different third- or higher-order statistics is shown in the upper illustration on the preceding page. One begins by drawing a triangle *KLM*. In the middle of one of its sides, say *LM*, a point *O* is placed. Line *OK* connects *O* with the opposite vertex *K*, and a line perpendicular to *OK* is drawn through *O*. Finally, two points, *P* and *Q*, are selected on this line such that *PO* is equal to *QO*. The micropattern *a* consists of four nonoverlapping disks of equal size with their centers at the points *K, L, M* and *Q*. The micropattern *b* consists of disks of the same size centered on *K, L, M* and *P*. The micropatterns *a* and *b* are used, with random rotations, to generate textures *A* and *B*. From the geometry of construction it is obvious that *QM* is equal to *PL, QL* is equal to *PM* and *QK* is equal to *PK*. Thus any distance between a pair of points on the disks of micropattern *a* has a corresponding equal distance between a pair of points on the disks of micropattern *b*. The dipoles between these pairs of points have the same length but different orientations for *a* and *b* respectively. This difference in orientation does not count, however, because the micropatterns are randomly rotated (pivoted through the point *O*). As a result the second-order statistics $f(r)$ (and, of course, the first-order statistics $f_0$) are identical for textures *A* and *B*. On the other hand, the reader can easily find three points that fall on micropattern *a* to form a triangle that has no counterpart on micropattern *b*. Hence the third-order statistics of textures made from *a* and *b* likewise differ.

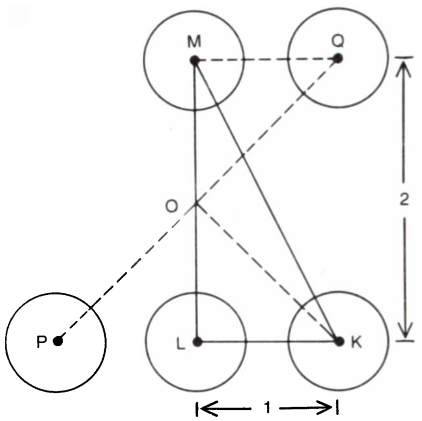
The important advantage of this method over using mirror-image micropatterns is that one can choose *KLM* triangles whose resulting micropattern pairs look quite different from each other. Thus the *KLM* triangle in the upper illustration on the preceding page generates an open *C*-shaped micropattern and a compact *Y*-shaped micropattern, which are impossible to confuse when they are viewed side by side. When the two textures are assembled into arrays, however, they are as hard to discriminate as the textures based on the letter *R* and its mirror image [*see array at left in lower illustration on preceding page*].

Up to this point I have not presented textures in which the positions of the micropatterns are randomized. The fact that texture discrimination is difficult, if not impossible, even with orderly spacing of the micropatterns tends to strengthen our conjecture about the limitation of the visual system. If we now randomize the position of the *C*-shaped and *Y*-shaped micropatterns (avoiding overlapping), discrimination becomes even more difficult, if not impossible [*see array in middle in lower illustration on preceding page*].

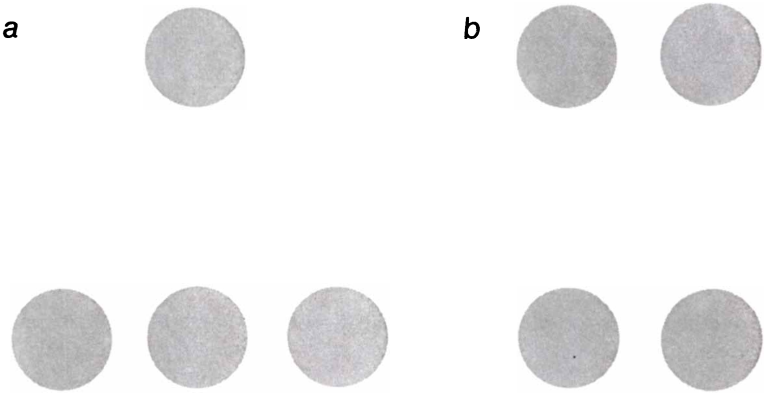
Texture discrimination becomes easier, however, if the images are slightly blurred, or thrown out of focus, because now the second-order statistics between the two textures become different [*see array at right in lower illustration on preceding page*]. The difference arises because the slightest blur can cause some "rounding off" in the areas where the disks are adjacent, thereby affecting the second-order statistics.

Our results with many observers have shown that some slight texture discrimination is possible when the micropatterns are derived from *KLM* triangles, whereas discrimination is totally impossible with, say, textures based on *R* and its mirror image. Thus the *KLM* textures might be regarded as weak counterexamples to our hypothesis that visual texture discrimination involves processes that cannot "compute" third- or higher-order statistics. Indeed, it would be going too far to believe texture discrimination depends entirely on the statistical properties of the textures alone, and to ignore all additional factors such as the idiosyncrasies of the various feature extractors.

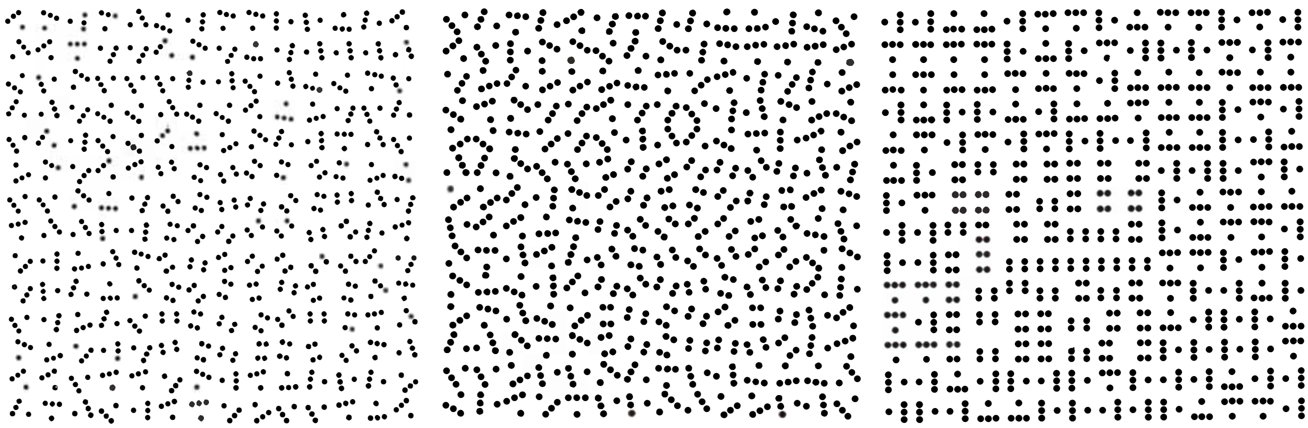
What would happen if we were to experiment with other *KLM* triangles that yielded simpler feature differences between the micropattern pairs, hoping thereby to see if the differences could be detected by the simplest kinds of line detectors? A micropattern pair with the desired simplicity is produced by the *KLM* triangle in the top illustration on the opposite page, suggested by my colleague William Tyler. The triangle is a right triangle in which the perpendicular sides are in the ratio 2 : 1. Micropattern *a* consists of four disks that form an inverted *T;* micropattern *b* consists of four disks that define the corners of a rectangle. One can imagine that the three colinear disks in micropattern *a* might serve to stimulate a thin line detector three times. Similarly, micropattern *b* might serve to stimulate a thick



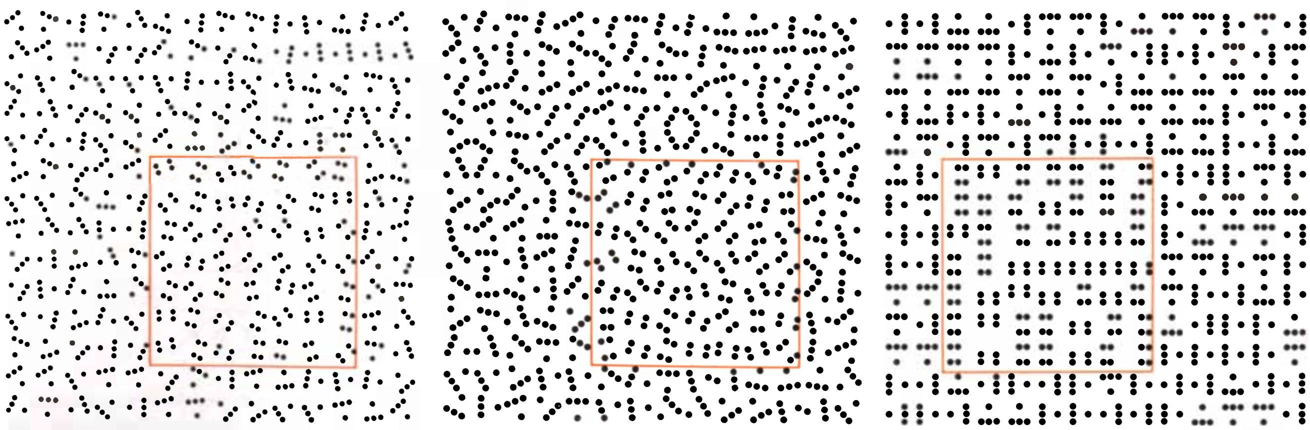

ANOTHER PAIR OF MICROPATTERNS that yield pairs with identical second-order statistics form an inverted *T* and a rectangle.




It was expected that such micropatterns might stimulate "line detectors" of the type known in visual systems of cats and monkeys.



THREE TEXTURE PAIRS are based on the inverted-*T* and rectangle micropatterns depicted in the illustration above this one. In the example at the left the micropatterns are randomly rotated on regularly spaced centers; the discriminability of the texture pairs is very weak. In the middle example the micropatterns are randomly jittered without any overlap, making discrimination still more difficult. With these particular micropatterns random orientations are necessary. Otherwise, as in the example at the right, in which the micropatterns are regularly spaced and are limited to two rotations (0 degrees and 90 degrees), the dots may form long horizontal and vertical sequences that are quite different for the two textures even though their second-order statistics are the same.



LOCATION OF EMBEDDED TEXTURE in each of the texture pairs in the illustration above this one is indicated by a thin color outline. It is surprising that even with this perceptual assistance the textures themselves are still rather difficult to discriminate.

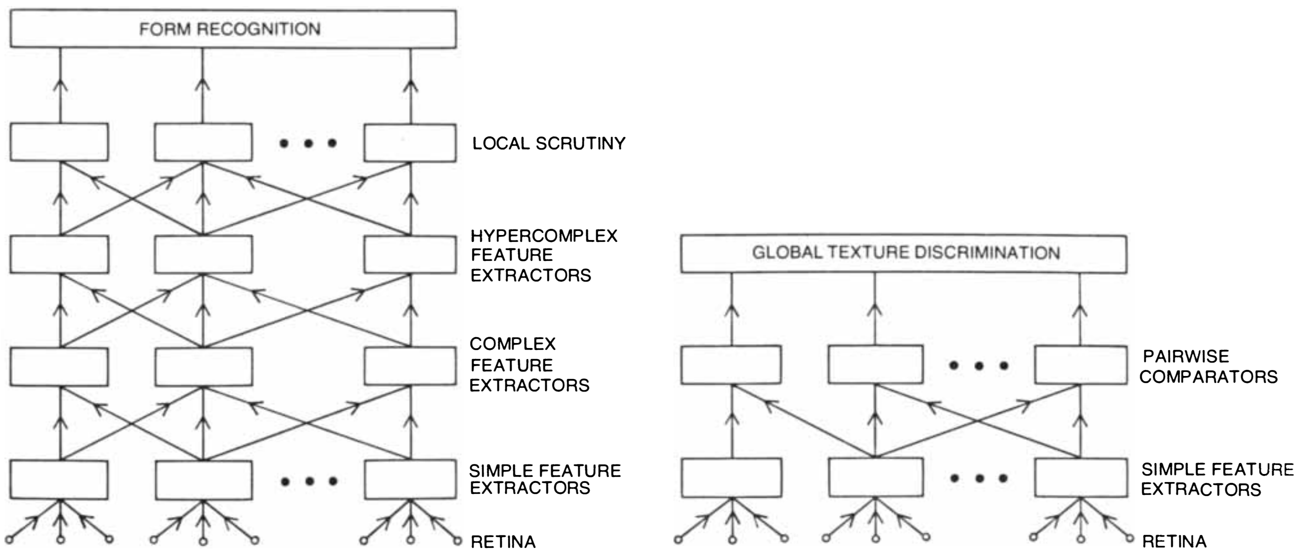
line detector (of the same length) four times. Therefore if the visual mechanism of texture discrimination were to employ simple line detectors, they should be able to differentiate between textures composed of the "thin" clusters of micropattern *a* and the "thick" clusters of micropattern *b*.

The middle illustration on the preceding page shows three pairs of textures generated by micropatterns *a* and *b*. Contrary to the prediction of the line-detector hypothesis, texture discrimination is not notably stronger in the left and middle texture pairs than it is in the texture pairs composed of the *C*- and *Y*-shaped micropatterns. In the left texture pair the micropatterns are regularly spaced but are rotated in all possible orientations around point *O* in the *KLM* construction diagram. In the middle texture pair the two micropatterns are randomly thrown but are not allowed to overlap. As one would expect, texture discrimination is made still more difficult by the randomization. In forming textures from these particular micropatterns it is important to jitter the patterns randomly, since the disks in micropattern *b* are capable of forming long horizontal and vertical sequences in a manner not possible with micropattern *a*. These sequences are readily visible even though the second-order statistics are still identical for both textures. This is demonstrated in the texture pair at the right in the middle illustration on the preceding page, where the micropatterns *a* and *b* not only are regularly spaced but also are allowed only two rotations: 0 degrees and 90 degrees. Even so the eye does not spontaneously perceive that texture *B* fills a square in the lower left quadrant of the total array. To sum up, simple dot detectors and line detectors, which are believed to exist in the human visual system, evidently contribute something to texture discrimination, but they contribute surprisingly little.

Perhaps the most interesting outcome of these demonstrations is not that simple feature extractors can sometimes discriminate between textures with higher than second-order statistics owing to some local feature formed by chance, but rather that the many complex and hypercomplex feature extractors present in the visual system do not facilitate pure perception in texture discrimination. Thanks to a hierarchy of increasingly complex feature extractors a pattern can be analyzed in minute detail, but for texture discrimination only the simplest feature extractors come into play; moreover, the outputs of these extractors are evidently compared only in pairs.

These hypotheses about the visual system are depicted schematically in the illustration below. The diagram at the left shows the retina and a hierarchical level of feature extractors of increasing complexity. (Whether the increasingly complex feature extractors actually get their multiple inputs from the preceding stage of feature analyzers or from much earlier stages is not important in this context.) The analyzers at the highest level constitute the form-recognizer stage that effectuates scrutiny of any local micropattern. The diagram at the right in the same illustration represents a model of the global (as opposed to the local) texture-discrimination network that employs only the earliest stages of feature extractors, that is, the simplest units, and only pairs of these elements are connected to the comparison units whose outputs are combined by the texture-discrimination processor. (If more than two simple units were connected to the next stage, the network could process statistics higher than second-order statistics.)

According to this model, the comparison units and their combinations have a structure that computes second-order statistics. It may be that for texture discrimination complete second-order statistics are not necessary, only some statistical parameters that can be derived from them. Indeed, there are some special cases where texture pairs with different second-order statistics cannot be discriminated. For example, in the illustration on the opposite page micropattern *b* is simply the mirror image of micropattern *a*. Since *a* and *b* are not randomly rotated in all possible orientations, they obviously have different second-order (dipole) statistics, yet the two textures resist discrimination. We conclude, therefore, that the texture-discrimination mechanism can at most compare the output of two simple extractor units. Conceivably the texture-discrimination process takes only the first-order




**NEUROPHYSIOLOGICAL MODELS incorporate the author's conclusions about the levels of visual information processing required for detailed form recognition, or local scrutiny (*left*), and global texture discrimination (*right*). In detailed form recognition visual information received at the retina passes through a hierarchy of feature extractors, culminating in recognition. Global discrimination seems to employ only simple feature extractors whose outputs are combined in pairs by a texture-discrimination processor.**

statistics of various simple feature extractors that can be pooled according to diameter or to width, length and orientation.

Do animals share human perceptual limitations? Obviously I do not mean limitations in retinal resolution (a falcon's visual acuity, for example, is known to exceed our own) but limitations in perceptual processing power. It could be argued, for instance, that the processing power of our visual system should exceed that of other animals because our brain is structurally more complex. On the other hand, one could counter, we can afford to have a less powerful perceptual system because we can always implement its shortcomings with the symbolic processes of language, logic and mathematics. Lacking these processes, animals might have been forced to evolve a more powerful perceptual machinery that enables them to compute statistics higher than second-order statistics.

The question could be decided by conducting texture-discrimination experiments, using patterns of the type discussed here, with animals in the laboratory. Even before attempting such an investigation one can get some preliminary answers by exploiting the fact that nature has been conducting such experiments for aeons. Animal camouflage is based on the perceptual limitations of predators. Some animals, through evolutionary selection, exhibit a replica of the color and texture of their natural environment as it is perceived by their enemies. It is well known that human beings have much difficulty discriminating camouflaged animals from their natural background. For example, the light-colored peppered moth is almost invisible when it is resting on the light-colored bark of an oak tree.

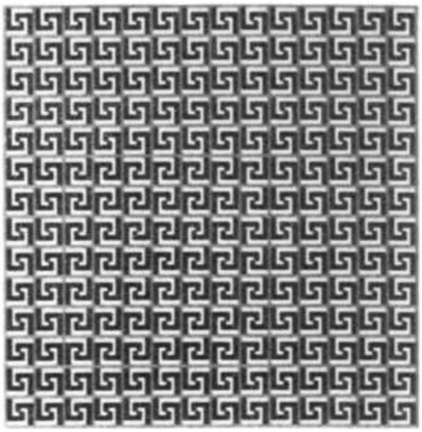
Such difficulties in discrimination suggest that our perceptual system does not surpass the perceptual mechanisms of all the predatory animals whose camouflaged prey is also invisible to us. Whether or not some of these animals actually excel us in perceptual ability remains to be seen. It seems most unlikely, however, that the texture of a camouflaged moth and the texture of bark have identical third-order statistics in addition to identical second-order statistics. Only if we were able to find animals that mimicked their environment to the third order in their appearance could we conclude that their predators possessed a global perception superior to our own.

Let me clarify a few questions that are often asked about the material covered in this article. One frequent question is: Could one perhaps learn to improve one's texture discrimination by noticing statistical properties higher than those of the second order? The reader will remember that some of the textures presented here included such highly familiar micropatterns as the letters *U* and *R*, yet when these letters are used to form textures, they do not yield better texture discrimination than unfamiliar patterns do. Thus we can be quite confident that learning has no effect. What happens is that with familiar micropatterns it is more difficult to refrain from local scrutiny. As long as we can adhere to this taboo, however, texture discrimination is not aided by familiarity.

A related question is: Why do I regard scrutiny in texture discrimination as a cognitive process? Even if scrutiny meant only the local form recognition of, say, a letter *R* or its mirror image, it is a question of taste whether the reading of the alphabet is a perceptual process or a cognitive one. When we try to decide the shape of an area that is composed of certain letters, however, we have to augment local form recognition with a letter-by-letter scan and have to memorize the trace of the boundaries between different letters. This compound task of form recognition, scanning and memorizing is certainly more complex than pure perception.

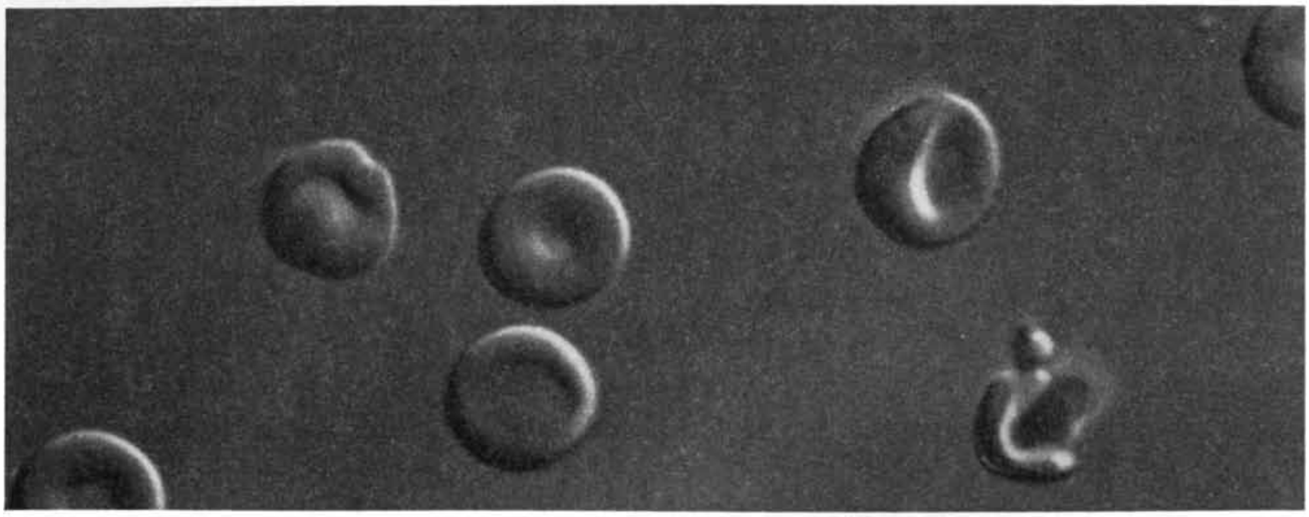
Another question is: Will the conjecture hold for textures with decreased micropattern densities and increased viewing angles? The reader can easily verify that texture discrimination in the demonstrations is not improved as one varies the viewing distance over a wide range. Of course, if the density of the micropatterns is greatly reduced and the array is viewed from close range, then too few micropatterns are presented in any instant, and instead of seeing the micropatterns as forming a texture one sees them in isolation, which leads to local scrutiny.

This brings us to the main question: Why did two systems evolve in vision, one for the local scrutiny of form and the other for global perception? The answer lies in the fundamental dichotomy of perception that separates things into "figure" and "ground." Any object in our environment can be seen either as figure or as ground, but it can be seen only one way at a time. This point can be illustrated by an example. Imagine that we are told we will witness a crime in a brief motion-picture scene and that we are asked to concentrate on the criminal for later identification. To our surprise the experimenter asks us instead to describe the texture of the background. Although we might be able to describe the criminal in great detail, we are able to report only some vague properties of the background (for example its color or granularity). Indeed, all we are able to report about textures we have not selectively attended to is governed by first- and second-order statistical constraints. Hence "selective attention" separates figure from ground and local form recognition from global texture perception. It is interesting that children suffering from dyslexia, many of whom are highly intelligent but have difficulty reading, also have problems with perceptual attention and often confuse letters with their mirror images. When we agreed in the framework of texture discrimination to refrain from local scrutiny, we too in a sense became dyslexic, and it is no wonder that we could not discriminate between texture pairs made up of letters and their mirror images.

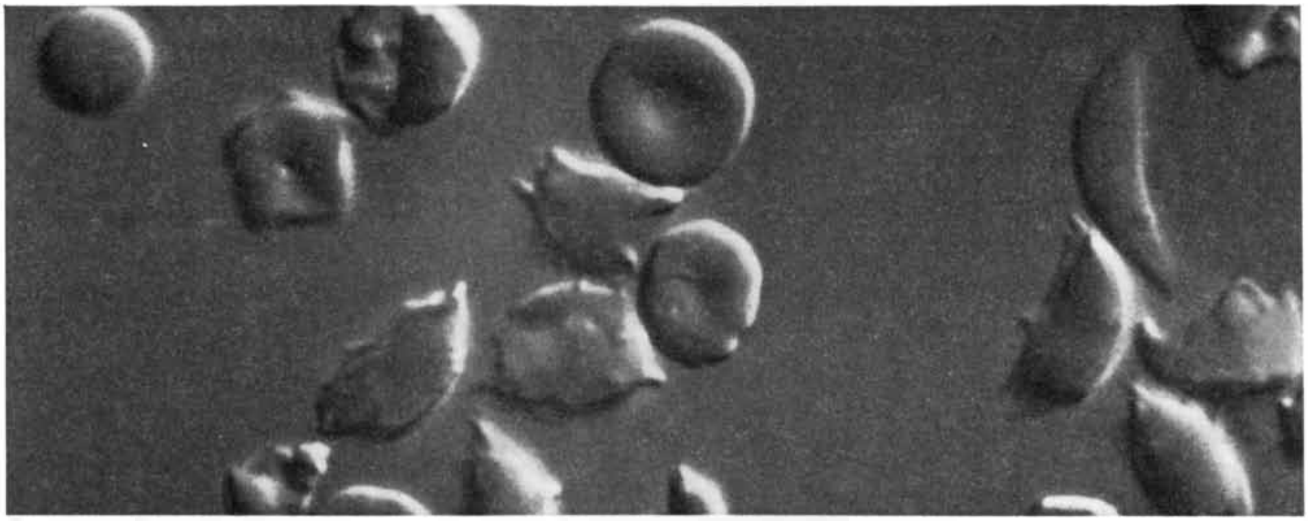


**SPECIAL CASE shows that a texture pair may resist discrimination even when the second-order statistics of the two textures are different. Here micropattern *b*, which forms the texture of the small embedded square, is a mirror image of micropattern *a*, which forms texture of large surrounding square. Since micropatterns are not randomly rotated, dipole statistics are not identical.**

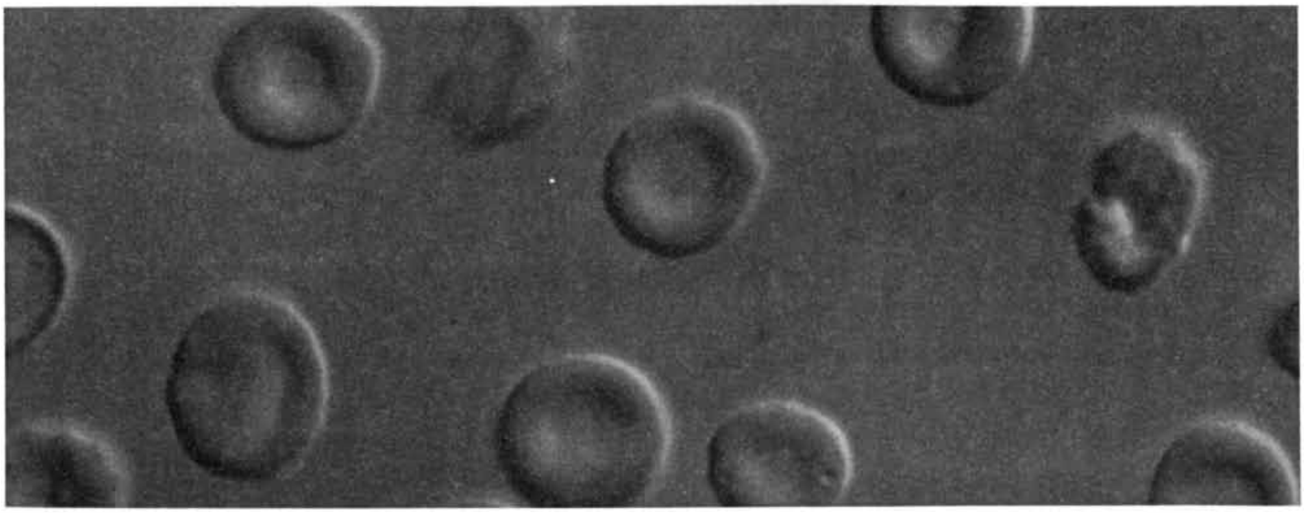
Thus we can regard global texture discrimination as a very general process, encompassing the perception of all things that fall outside the limelight of our attention. Until now it has been said that all unattended objects at a given instant formed a ground; now we can say that they form a texture. Therefore as long as the conjecture holds for texture perception we can endow ground perception with the properties and limitations of texture perception.



**OXYGENATED RED BLOOD CELLS** from a patient with sickle-cell anemia are shown enlarged 1,600 diameters. In the presence of oxygen most of the cells have the same shape as normal red blood cells. Only the cell at the lower right is abnormal in shape.



**DEOXYGENATED CELLS** from a sickle-cell patient exhibit a variety of bizarre shapes. The upper cell at the far right has the classic sickle shape for which the disease was named. Most of irregularly shaped cells regain normal shape in presence of oxygen.



**CYANATE-TREATED CELLS** from a sickle-cell patient are shown after removal of oxygen. Most of the cells have retained the normal shape. These micrographs were made with differential-interference contrast microscope by James Jamieson of Rockefeller University.

# CYANATE AND SICKLE-CELL DISEASE

## The abnormal hemoglobin of people who suffer from sickle-cell anemia is made to behave like normal hemoglobin in experiments with the administration of the simple chemical sodium cyanate

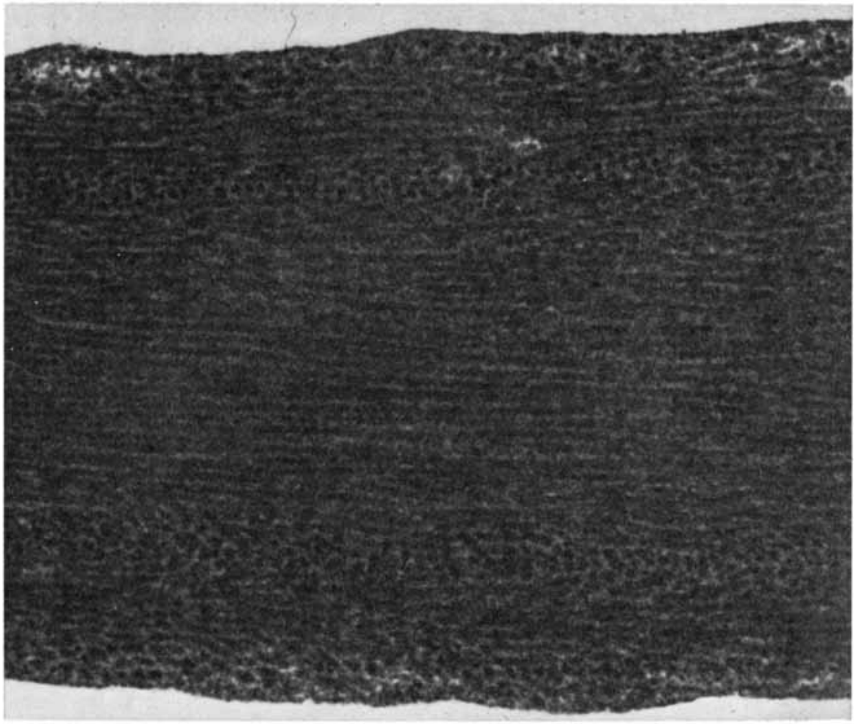
by Anthony Cerami and Charles M. Peterson

Sickle-cell anemia was the first disease to be understood at the molecular level. This hereditary disorder is caused by the presence of an abnormal form of hemoglobin, the iron-containing protein in red blood cells that transports oxygen from the lungs to other tissues. The disease manifests itself when a child inherits two genes, one from each parent, for the abnormal hemoglobin. There are two potential approaches to treating genetic diseases of this kind. The first is to change the genetic material itself, and in the future techniques may be developed that will make such changes possible. The second is to modify the abnormal product of the flawed gene so that the product functions more normally. Such modification could be accomplished by attaching a specific molecule to the abnormal gene product, which is usually a protein. The feasibility of the molecular approach is currently being demonstrated in the treatment of sickle-cell anemia. Here we shall describe how the discovery came about that the sickling of red blood cells can be prevented simply by attaching a common chemical, cyanate, to the defective molecule of hemoglobin in people with sickle-cell disease.

If a person inherits a gene for the abnormal sickle-cell hemoglobin molecule from one parent and a gene for the normal molecule from the other parent, he does not show the symptoms of sickle-cell anemia but is said to carry sickle-cell trait. It is thought that people with sickle-cell trait are more resistant to malaria than noncarriers and therefore have a better chance of survival in regions where malaria is endemic. Indeed, the proportion of the population with sickle-cell trait in malarial regions of central Africa can be as high as 40 percent. Africans were probably aware for centuries of sickle-cell disease in some of their children. The ethnic group that speaks the Ga language called it *chwechweechwe* because of the crying noises the children made during the painful episodes of the disease.

Today sickle-cell trait and sickle-cell anemia are found predominantly in the black populations of the world. It is estimated that the trait is carried by 8 to 10 percent of the black population in the U.S. Of every 1,000 black infants born in the U.S. three have sickle-cell anemia. The trait is also known in the populations of the Caribbean, Central America and parts of South America. It is found in small pockets in Turkey, Greece, the Middle East and India. Migrants and slaves from Africa probably carried the trait to those regions.

Sickle-cell disease was first clinically described in 1910 by James B. Herrick, a Chicago physician. One of his patients, a black West Indian student, complained of recurrent pains, fever, coughing and dizziness. Giving the patient a comprehensive examination, Herrick found that he had anemia, leg ulcers, jaundice and joint disease. He also observed that some of the patient's red



**IRREVERSIBLY SICKLED RED CELL** is seen in section enlarged 80,000 diameters. The long fibrils are chains of polymerized hemoglobin molecules, which are responsible for the rigidity of sickled cells. The dots are fibrils seen end on. Electron micrograph was provided by John F. Bertles of the Columbia University College of Physicians and Surgeons.

blood cells were not round but crescent-shaped, and he named them sickle cells. The recurrent severe pain, which is an acute phase of the disease, is called sickle-cell crisis. Many people suffering from sickle-cell disease die in their first few decades of life, although a small number survive beyond the age of 50.

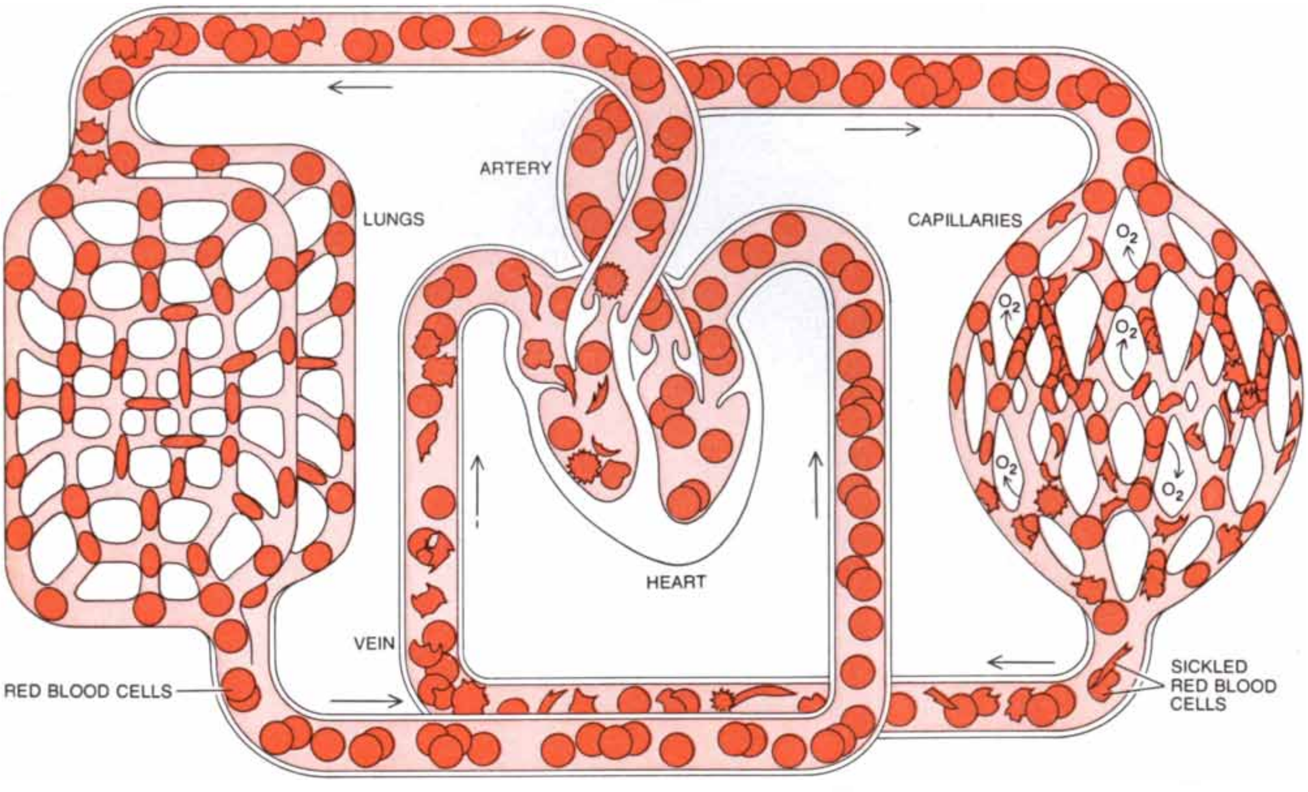
The first insight into the cause of the disease came in 1927, when E. V. Hahn and E. B. Gillespie of the Indiana University School of Medicine observed that the sickling of red blood cells is reversible, depending on the oxygen content of the blood. When the oxygen content is high, most of the red cells in the blood of someone with sickle-cell anemia are round. When the oxygen content is lowered, the red cells assume a variety of bizarre shapes but not necessarily the sickle shape that was originally described by Herrick [*see illustrations on page 44*]. When the oxygen content is restored, most of the red cells return to their original shape. The few that do not are called irreversibly sickled cells.

Hahn and Gillespie proposed that sickling occurs in the capillaries when red cells give up oxygen to the surrounding tissue. In addition to their jagged shape sickled cells develop a rigidity that interferes with their passage through the capillaries. This rigidity is the result of an aggregation of abnormal hemoglobin molecules in the sickled cell. The molecules combine with each other to form quasi-crystalline structures that push the red cells into abnormal shapes [*see illustration on preceding page*]. If the sickled cell is trapped in a capillary, it blocks the passage of other red cells, which in turn sickle when they give up their freight of oxygen. It is this clogging of the small blood vessels by sickled cells that is responsible for many of the clinical problems associated with sickle-cell anemia.

The next important advance in the understanding of sickle-cell disease came in 1949, when Linus Pauling demonstrated that it was an abnormal hemoglobin molecule, now designated hemoglobin S, that was responsible for the sickling process. With this demonstration he originated the concept of molecular disease. Working at the California Institute of Technology with Harvey A. Itano, Samuel J. Singer and Ibert C. Wells, Pauling also found that when an electric current is passed through a solution of hemoglobin, normal hemoglobin migrates faster toward the positive electrode than hemoglobin S.

Within a few years the exact location of the defect in the hemoglobin S molecule was identified. The hemoglobin molecule consists of four chains of amino acids: two identical alpha chains and two identical beta chains [*see top illustration on opposite page*]. In the alpha chain there are 141 amino acids; in the beta chain there are 146. Vernon Ingram, who was then working at the University of Cambridge, showed that the only difference between normal hemoglobin and hemoglobin S is the substitution of valine for glutamic acid at the sixth position on the beta chains. The mobility in an electric field of normal hemoglobin differs from that of hemoglobin S because the glutamic acid at the sixth position on the normal beta chains has a negative charge and the valine in hemoglobin S has no charge.

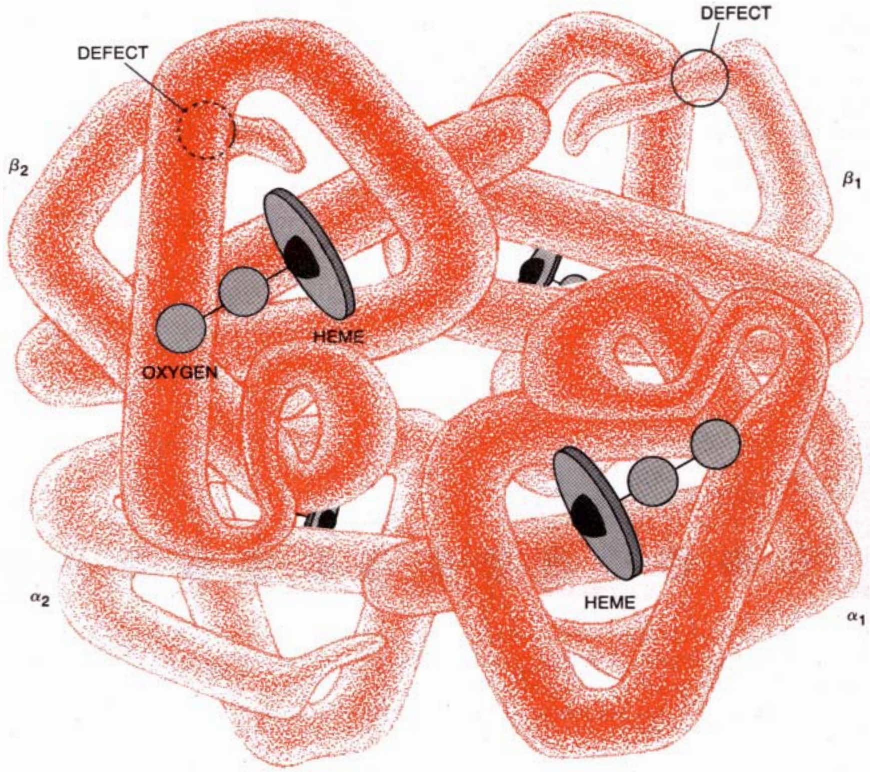
Organic molecules with an electric charge generally attract water and are therefore called hydrophilic. Organic molecules with no electric charge generally repel water and are called hydrophobic. When it was found that hydrophobic valine replaces hydrophilic glutamic acid in hemoglobin S, Makio




**SICKLING CYCLE in the circulatory system of a person with sickle-cell disease is depicted schematically with the red cells enlarged. When the abnormally shaped red cells pick up oxygen in the lungs, they regain their normal circular shape. When these cells give up their load of oxygen in the capillaries of tissues, however, they assume jagged shapes and become rigid. Some of the sickled cells are trapped in the capillaries and block the passage of other red cells, which also sickle as they give up their oxygen. It is the clogging of small blood vessels by sickled cells that is responsible for the painful symptoms experienced by those who suffer from the disease.**

Murayama of the National Institutes of Health postulated in 1966 that it is the hydrophobic bonds that are responsible for the aggregation of hemoglobin S molecules.

It is known that weak hydrophobic bonds can be disrupted by certain chemicals, for example urea. With this fact in mind Robert M. Nalbandian of Blodgett Memorial Hospital in Grand Rapids, Mich., undertook to treat sickle-cell anemia by infusing large amounts of urea into patients with sickle-cell disease. The initial results looked promising: patients given urea during sickle-cell crisis were reported to have shown some improvement. There was, however, a major problem. If the hydrophobic bonds between the molecules of hemoglobin S are to be broken, the concentration of urea in the blood has to be kept high. And since urea is a normal waste product of metabolism and is steadily cleared from the blood by the kidneys, it is almost impossible to attain and preserve the necessary high level of urea in the patient. A two-year study of the effectiveness of the urea treatment ended with disappointing results, and the treatment was dropped.




**HEMOGLOBIN MOLECULE consists of four protein chains: two identical alpha chains (*$\alpha_1$ and $\alpha_2$*) and two identical beta chains (*$\beta_1$ and $\beta_2$*). The defect in hemoglohin that causes red cells to sickle is located near the tip of each beta chain. The iron-containing heme near the center of each of the four chains picks up oxygen in the lungs and releases it in the capillaries. There are some 280 million molecules of hemoglobin in one red cell.**

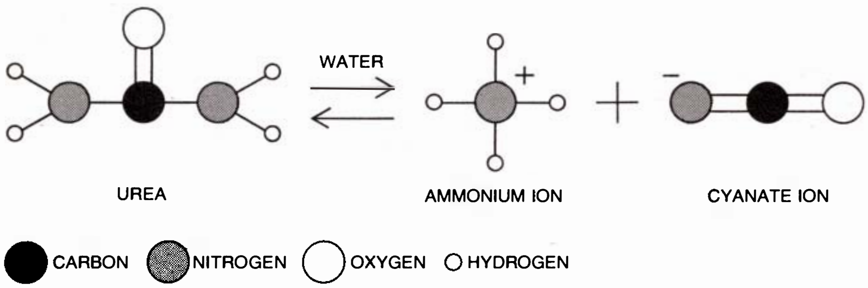
Although urea therapy was a failure in the treatment of sickle-cell disease, it did provide the impetus for the experiments that led to the discovery of the antisickling property of cyanate. James M. Manning and one of us (Cerami) suggested that it was not urea but cyanate that produced the positive results in Nalbandian's early tests. The relation between urea and cyanate has an important place in the history of chemistry. The synthesis of an organic compound from an inorganic substance was first achieved in 1828, when Friedrich Wöhler heated a salt, ammonium cyanate, and got urea. When urea is dissolved in water, cyanate is formed in the solution. It was not until 1960, however, that the importance of cyanate in urea solutions was realized. In a series of elegant experiments George Stark, William H. Stein and Stanford Moore of Rockefeller University observed that the small amounts of cyanate in such solutions reacted with functional groups in protein molecules. Since hemoglobin is a protein, we decided to test the effects of cyanate on sickle cells.

Our first experiment was simply to add cyanate to a test tube that contained red blood cells from a patient with sickle-cell anemia. After a period of incubation the oxygen was removed from the solution in the test tube. Many of the red cells retained their normal shape instead of sickling. The inhibition of sickling continued even after the unreacted cyanate was washed out of the solution.

Chemical analysis of the cyanate-treated cells revealed that the cyanate had reacted with the terminal amino group of the hemoglobin molecule. Once the reaction occurs it is irreversible, that is, the cyanate stays on the hemoglobin for the lifetime of the molecule. The reaction of cyanate with a larger molecule is termed carbamylation.

The structural similarity between a molecule of cyanate and a molecule of carbon dioxide is striking [*see lower illustration on next page*]. And like cyanate, carbon dioxide reacts specifically with the terminal amino group of hemoglobin. The carbon dioxide reaction, however, is reversible, and in the lungs the carbon dioxide is given up by the hemoglobin. It is estimated that 30 percent of the carbon dioxide released in the tissues by metabolic processes reacts with terminal amino groups of hemoglobin and is carried to the lungs.

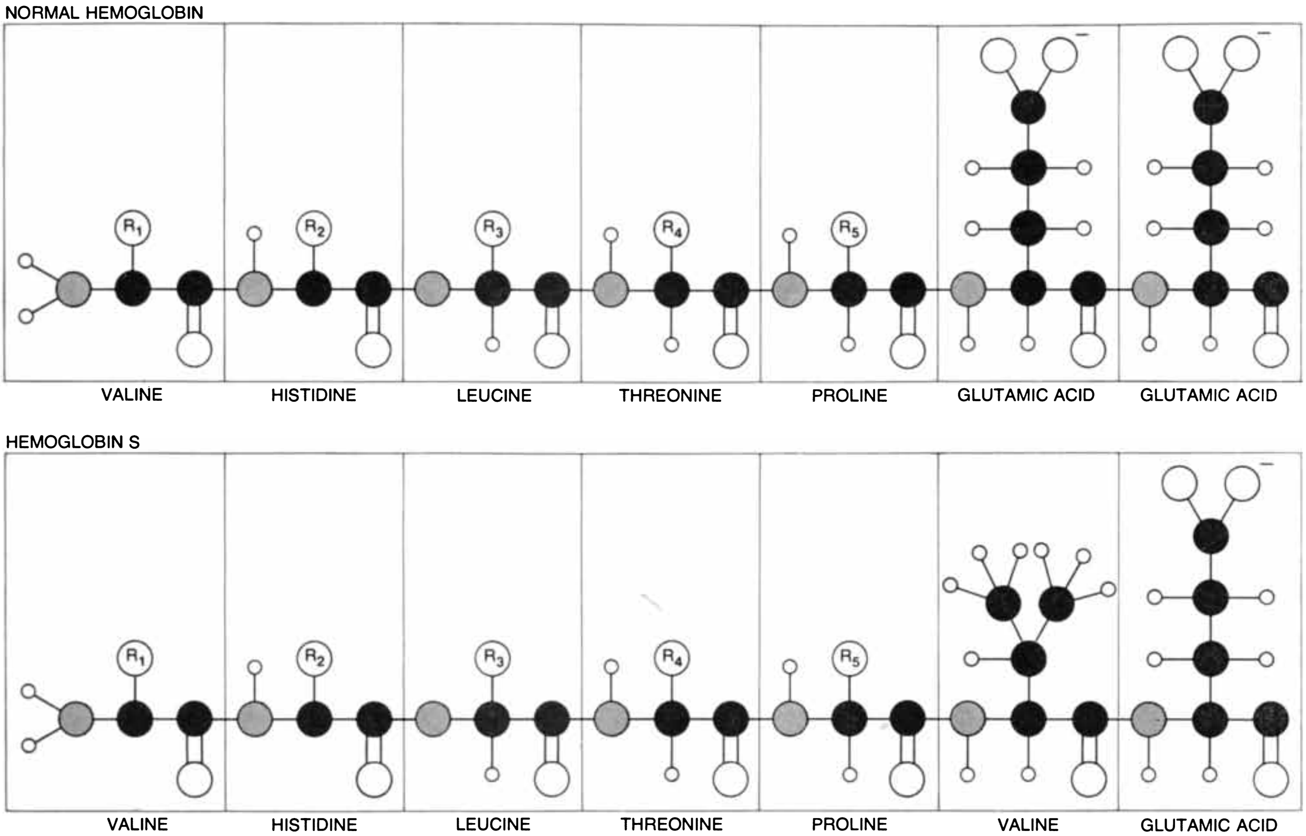
After the initial finding of the antisickling property of cyanate an evalua-



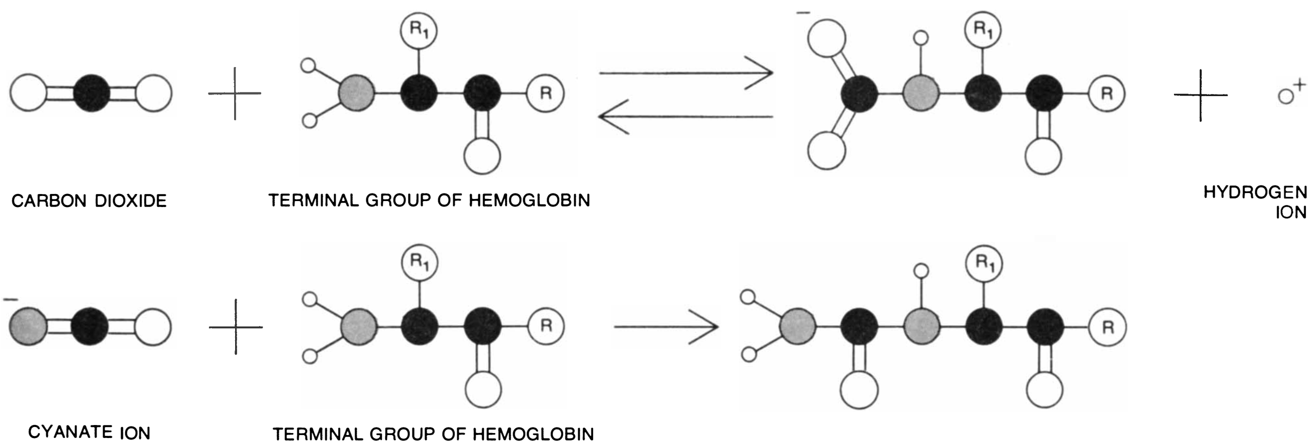

**CYANATE ION is formed when urea is dissolved in water. Attempts to treat sickle-cell disease with urea initially produced promising results, but later tests showed that the treatment was ineffective. The realization that cyanate is present in urea solutions led to the idea that the positive results in the urea treatment might have been due to cyanate. Subsequent tests with sodium cyanate resulted in the discovery of the antisickling properties of cyanate.**

tion of the compound was undertaken to determine its potential usefulness in the treatment of sickle-cell anemia. First it was necessary to show that the cyanate had no adverse effects on the red blood cell. Then a lack of toxicity in several animal species had to be documented. Frank de Furia and Denis Miller of the Cornell University Medical College were the first to show that cyanate was not toxic to human red cells. They demonstrated that there was no change in the activity of the metabolic enzymes in red cells when they were incubated with cyanate.

It was found that the affinity for oxygen of both normal hemoglobin and hemoglobin S increased in proportion to the amount of cyanate that had reacted with the hemoglobin. This increase means that at a given pressure of oxygen a larger number of hemoglobin molecules have oxygen molecules attached to them. The presence of oxygen on the




**FIRST SEVEN AMINO ACIDS** of the beta chain of normal hemoglobin and hemoglobin *S*, the abnormal hemoglobin that causes sickling, are shown for purposes of comparison. The two chains are identical except for the substitution of valine for glutamic acid in the sixth position on the beta chain of hemoglobin *S*. Glutamic acid has a positive charge and is hydrophilic, that is, it attracts molecules of water. Valine has no electric charge and is hydrophobic, that is, it repels water. The hydrophobic bonds are believed to be responsible for the aggregation of hemoglobin *S* molecules. *R* stands for side chains attached to first five amino acids.



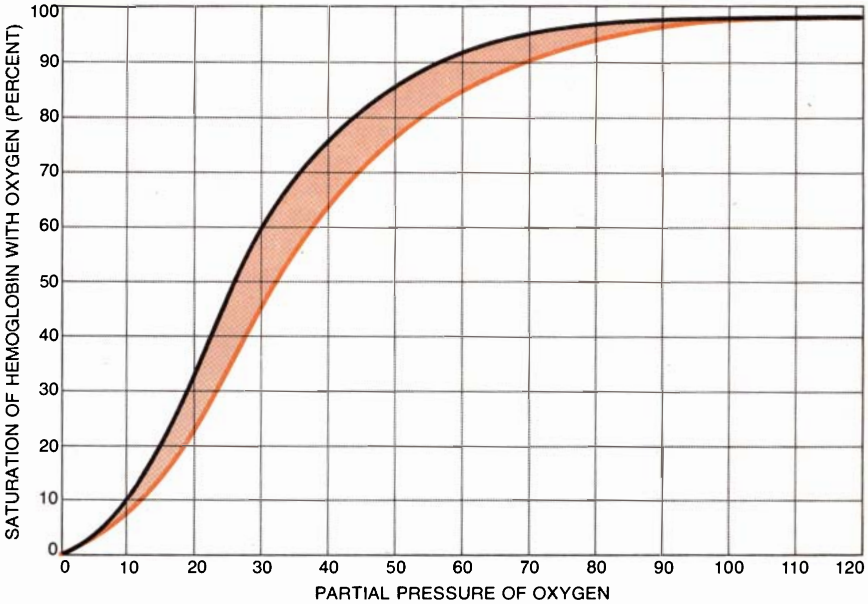

**TERMINAL AMINO GROUP OF HEMOGLOBIN** reacts with carbon dioxide given off by tissue cells. The carbon dioxide is carried to the lungs, where it is released. Cyanate, which is similar in structure to carbon dioxide, reacts with the same terminal group. Unlike the carbon dioxide reaction, the cyanate reaction is not reversible. The cyanate remains attached to the hemoglobin until the red blood cell dies. The antisickling action of cyanate is the result of its ability to increase hemoglobin's affinity for oxygen.

hemoglobin S molecule is believed to account for some of the antisickling action of cyanate. It was feared, however, that the increased affinity of hemoglobin for oxygen would create a problem. If the hemoglobin could not unload proper amounts of oxygen in the tissues, the result would be a functional anemia. Fortunately studies with experimental animals showed that blood treated with cyanate was capable of delivering oxygen to the tissues in sufficient quantity.

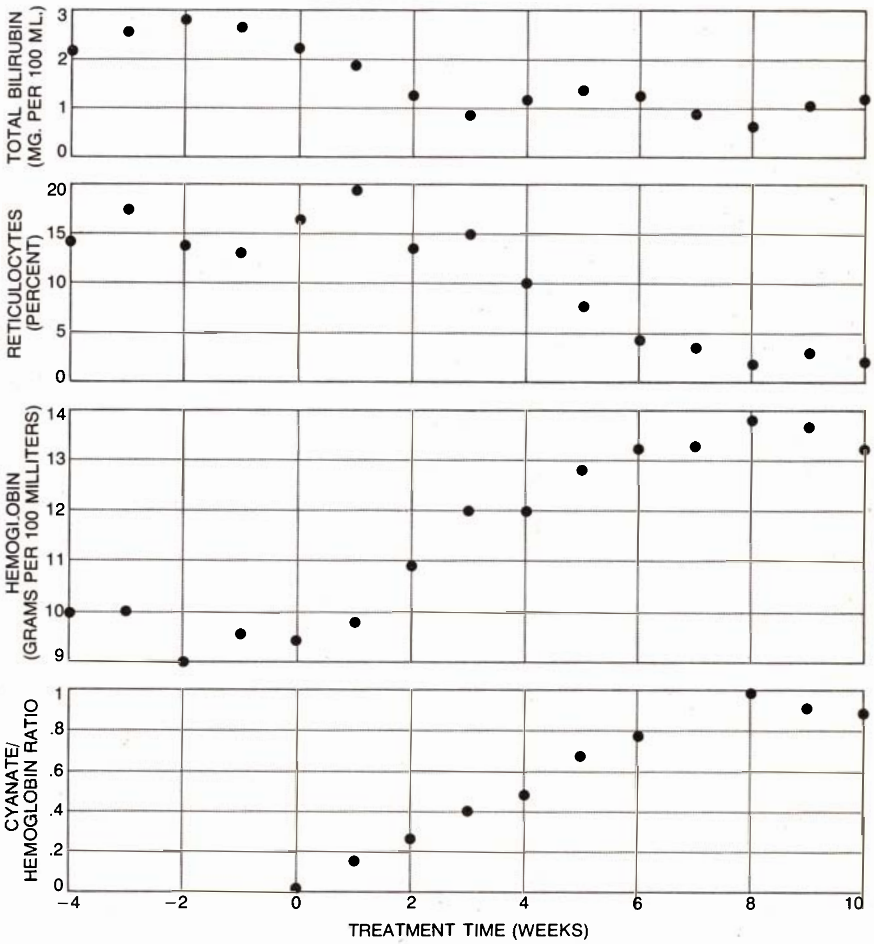
The first experiment with human patients was designed to answer the question: Does the antisickling property of cyanate observed in the test tubes persist when cyanate-treated cells are returned to the patient's circulatory system? The crucial experiment was conducted in collaboration with Peter N. Gillette and Manning at the Rockefeller University Hospital [*see illustration on next page*]. A small amount of blood was taken from a sickle-cell patient and treated with sodium cyanate. The red cells were then labeled with atoms of the radioactive isotope chromium 51. The radioactive chromium enabled us to measure how quickly the cyanate-treated cells were destroyed in the body. After the blood sample was reinfused into the patient we extracted small samples of blood at regular intervals and measured the amount of radioactivity present. We found that the cyanate treatment increased the rate of red-cell survival substantially.

The next step was to decide how to administer cyanate to patients with sickle-cell disease. There are two major possibilities. The first is to withdraw a quantity of blood from the patient, react the red cells with cyanate, wash the cells free of unreacted cyanate and return the blood to the patient. The second method is to administer the drug orally or by injection. Each method has advantages and disadvantages. The extracorporeal treatment is the safest because unreacted cyanate does not enter the body and cause undesirable side effects. The procedure is time-consuming and expensive, however, and can benefit only a relatively small number of patients. Of the estimated two million people in the world with sickle-cell disease only a small minority would have access to the necessary facilities.

We therefore embarked on an investigation of the oral administration of sodium cyanate. With the approval of the Food and Drug Administration a small-scale clinical evaluation was undertaken to assess the toxicity and benefits of the drug. Sodium cyanate in a capsule was




**OXYGEN SATURATION** of normal hemoglobin (*black curve*) and of hemoglobin *S* (*colored curve*) are shown. When blood from a sickle-cell patient is treated with cyanate, the oxygen saturation of hemoglobin *S* increases (*light colored area*). When every molecule of hemoglobin in the blood has reacted with cyanate, the saturation curves become identical.



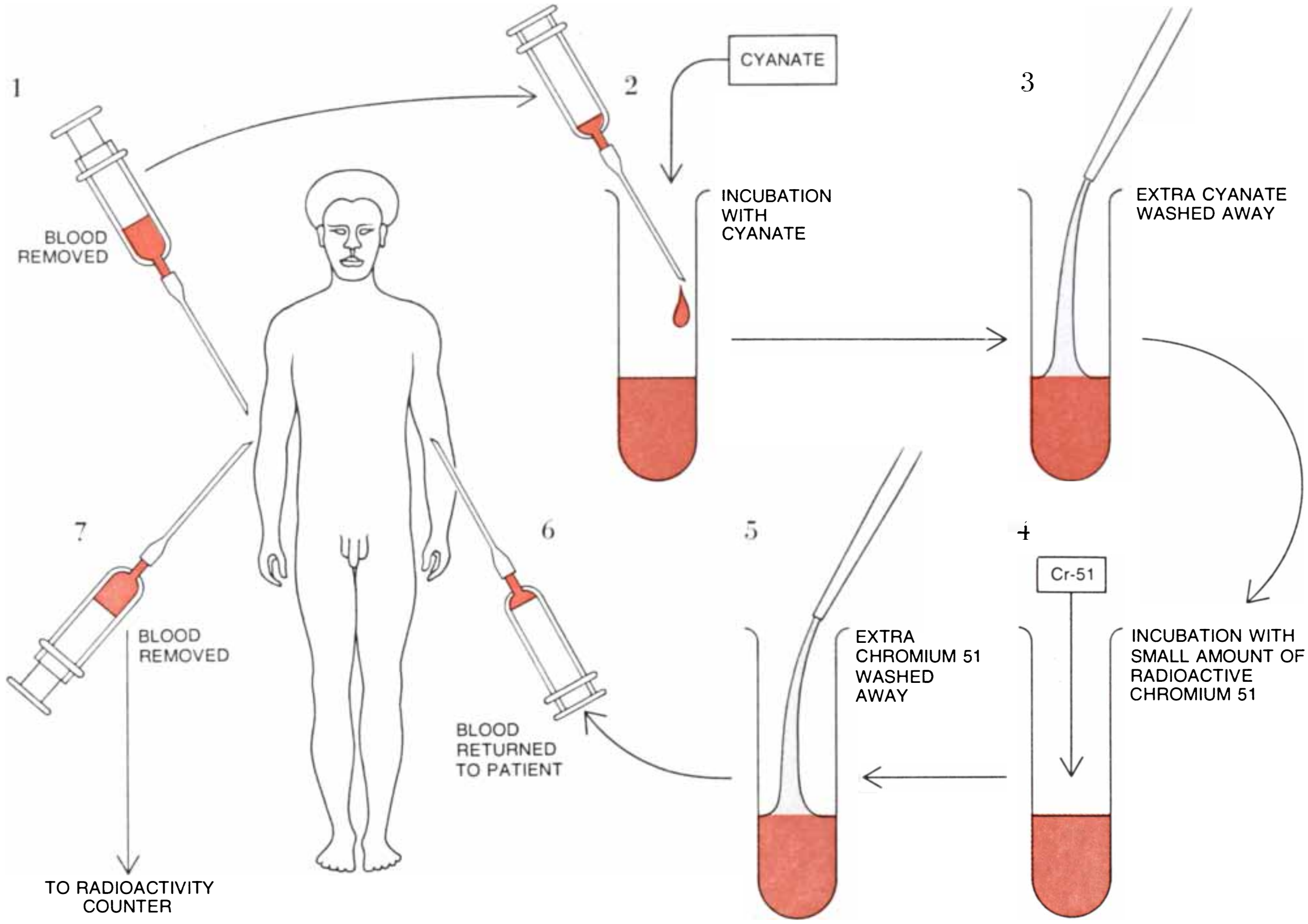

**RESPONSE OF PATIENT TO CYANATE** is recorded. As the amount of cyanate that is attached to hemoglobin increases, the total amount of hemoglobin in the blood also rises and approaches a normal level in about eight weeks. The number of reticulocytes (new red blood cells) falls, indicating production of new cells has returned to a normal level. The amount of bilirubin in the blood, a measure of how many red cells are dying, decreases.

given with food to patients in a selected group. The dosage was from 10 to 25 milligrams per kilogram of body weight. At such doses the cyanate did not give rise to any noticeable complications. Analysis of blood from the patients showed that the cyanate had reacted with the hemoglobin S molecules as it had been anticipated it would. We found that the red cells in the circulatory system lived longer following cyanate treatment, and that as a result the total number of red cells in circulation increased. The amount of increase varied with the patient but was significant with most patients. In addition the number of new red cells in circulation decreased, indicating that the production of these cells by the bone marrow had been reduced to a more normal level. In untreated patients with sickle-cell disease the number of new red cells in the blood is abnormally high because the bone marrow continuously strives to replace the cells that sickle and die.

Further investigation with higher doses of cyanate revealed a dosage limit and some complications. At doses higher than 35 milligrams per kilogram of body weight patients may lose their appetite and suffer weight loss. Some patients report nausea, gastrointestinal pain and drowsiness. In addition tingling, burning or weakness in the arms and legs may develop. All these symptoms disappear when the administration of cyanate is stopped.

As we have mentioned, people with sickle-cell anemia experience recurrent episodes of pain in various parts of the body during sickle-cell crisis. Pain is particularly difficult to evaluate, in view of the fact that the only measure of it is what the patient tells the physician. Our investigations nonetheless indicate that the frequency of painful episodes is decreased in patients treated with cyanate. The definitive double-blind trial that will be needed to prove this beneficial effect, however, remains to be conducted. In such a trial neither the physician nor the patient knows whether the capsule being taken contains the drug or an inert substance.

In the past 50 years the chemotherapy of infectious disease has made dramatic advances. One measure of this fact is the changing pattern in the hospitalization of children. Where once most of the pediatric admissions to hospitals in North America were for infectious diseases, today a majority are for the comparatively rare genetic diseases. Sickle-cell anemia, of course, is in the latter category. At the present time cyanate therapy for sickle-cell anemia can only be described as a hopeful new approach awaiting further evaluation to determine its clinical usefulness. Cyanate is nonetheless the first member of a new class of drugs: substances that modify an abnormal gene product so that it functions more normally. It has been proposed that such drugs be called chemometallactic, from the combining form for "chemical" and the Greek *metallaxis*, "modification."




**EXPERIMENT TO DETERMINE LIFE SPAN of cyanate-treated hemoglobin in a person with sickle-cell disease is schematically depicted. A small amount of blood was removed (*1*) and incubated with cyanate (*2*). After the extra cyanate was washed away (*3*) the blood was labeled with the radioactive isotope chromium 51 (*4*). The unreacted chromium was washed out (*5*), and the blood was returned to the patient (*6*). Blood was extracted from the patient every other day, and the amount of radioactivity was measured to determine how many of the cyanate-treated cells were still in circulation (*7*). It was found that the life span of the red blood cells that had been treated with cyanate was substantially increased as compared to the life span of red cells that had not been treated.**

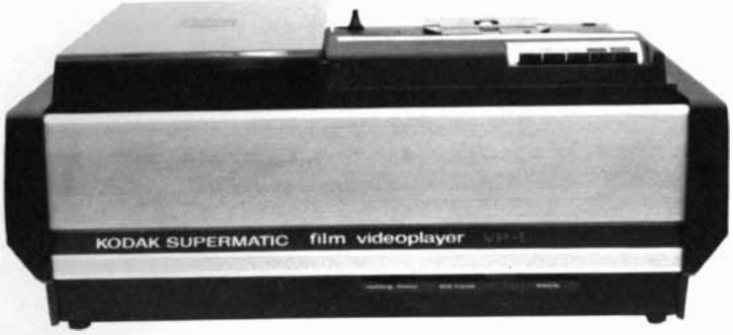
# We want to be useful ...and even interesting

## She moved on to another field

Marion Gleason came to Rochester in the early 20's as the wife of a musician employed by the founder of Kodak. After a bit, the company itself engaged her on the strength of her education in dramatic arts. We were in the process of introducing movie film only 16 millimeters wide. The movie industry, of course, ran on 35mm film. The lower cost would allow amateurs to make movies. Analogous to amateur dramatics. So the thinking ran. To show how it might be done, Marion Gleason wrote some scripts full of adventures such as the movie houses were showing. With large casts of friends she directed several productions.

As things turned out, large casts and thrilling airplane crashes proved unnecessary for enjoyment of home movies. With advances in emulsions, film width shrank to 8 millimeters, and 16mm became largely a professional medium. Later came super 8. Professionals in fields outside professional motion pictures have been turning to super 8.

As for Marion Gleason, she dropped out of dramatics altogether and turned to—of all things—toxicology. For many years she has been busy organizing increasingly voluminous editions of a standard compendium sometimes familiarly referred to in the world's poison control centers as, simply, the Gleason.




## Keep your options open

**This device takes super 8 film and puts out a good-quality color TV signal complete with sound, if any. You just connect its output cable to a TV receiver by the antenna terminal, or to a monitor, closed-circuit distribution system, broadcast station, or even videotape recorder. Compared with the alternatives for capturing action in color and sound, editing it, and showing it, super 8 film is simple, inexpensive, highly mobile. And it doesn't *have* to be shown on the film videoplayer if a common super 8 movie projector is available!**

**Further details from A. T. Brown, Dept. 640, Kodak, Rochester, N.Y. 14650.**

## The watching is easy

Perhaps a majority of all who are active today in science, teaching, technical marketing—persons who must communicate professionally and be communicated with—have been conditioned since childhood to regard the TV tube as just as reasonable an input to one's consciousness as ink on paper. That it takes a little less fuss to switch on TV than to set up a movie projector is hard to deny.

***Directory of KODAK Products and Services for the Health Sciences,* available from Dept. 55T, Kodak, Rochester, N.Y. 14650,** tells how to go about obtaining what we have to offer for the art of communication and other arts and sciences of biomedical interest.

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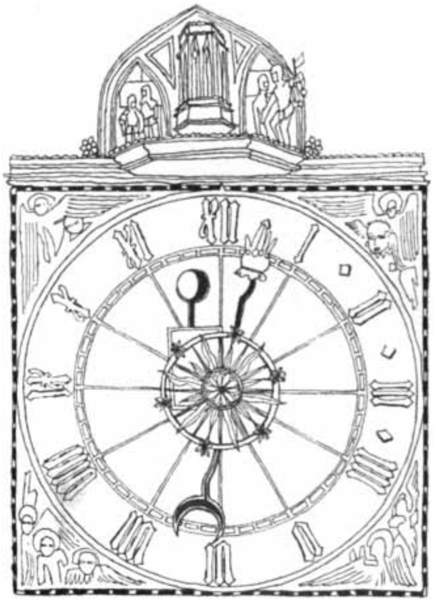
# SCIENCE AND THE CITIZEN



*Belt Tightening*

The prospect of sharply increased military expenditures—possibly surpassing $100 billion per year—in a time of general economic distress has focused renewed Congressional and public attention on the task of eliminating overly costly and expendable items from the record budget request made by the Department of Defense for the fiscal year 1976. As the chairman of the Senate Appropriations Committee, John L. McClellan of Arkansas, remarked recently: "The time has come when we must make a reassessment and a determination with respect to which weapons systems are absolutely essential to maintaining the deterrent that is imperative for our defense and survival."

In response to such calls the Center for Defense Information, an independent Washington-based research organization, has come forward with a specific proposal for cutting approximately $15 billion from the requested 1976 military budget "without jeopardizing national defense." The details of the plan are contained in a report published in the center's newsletter *The Defense Monitor*. In brief the recommended "Options for a Realistic Defense Budget" include: 1. Cancel the B-1 strategic-bomber program. 2. Stop spending on obsolescent new land-based intercontinental ballistic missiles (ICBM's). 3. Do not develop proposed new strategic cruise missiles. 4. Stop spending on new anti-ballistic-missile (ABM) systems. 5. Slow the Trident strategic-submarine program to one new boat per year. (One Trident submarine costs more than $1.5 billion.) 6. Set a ceiling of 10,000 on deployed strategic nuclear weapons. (If current Defense Department programs are allowed to go forward, the U.S. could have as many as 20,000 deployed nuclear weapons by 1985.) 7. Reduce overseas tactical nuclear weapons (currently estimated at more than 10,000). 8. Terminate obsolescent military alliances, such as the Southeast Asia Treaty Organization (SEATO). 9. Do not establish new foreign military bases. 10. Cut marginal overseas military forces, in particular the 66,000 U.S. soldiers now stationed in South Korea and Thailand. 11. Do not increase Army divisions beyond 13. (An expansion to 16 has been proposed.) 12. Cancel the program to build an Airborne Warning and Control System (AWACS). 13. Cancel the Surface-to-Air Missile (SAM-D) program. 14. Cancel the advanced XM-1 tank program. 15. Reduce operation and maintenance costs (which will reach almost $26 billion in fiscal year 1975). 16. Cut unnecessary military aid to other countries.

By adopting these and other measures, the center's staff estimates, the fiscal 1976 military budget could be held to about $85 billion, which would still be some $2.3 billion more than the Defense Department received for 1975.

*The 19.6-m.p.g. Car*

The three leading American automobile makers have assured the Federal Government that they will do their part to see that the average 1980-model car has a fuel economy of at least 19.6 miles per gallon, equivalent to an improvement of 40 percent over the 14 m.p.g. of 1974 models. In return for this offer of cooperation the Government has agreed to freeze the exhaust-emission standards for a five-year period, 1977–1981, at levels less stringent than those scheduled to go into effect in the 1977-model year but equal to the present stricter California standards (except for oxides of nitrogen, which would remain at the present Federal level). The Government also told automobile manufacturers that new Federally mandated safety standards would not add more than 100 pounds to the average car through the 1980-model year.

The Government's request for voluntary cooperation in improving fuel economy was embodied in a January letter to manufacturers from Secretary of the Interior Rogers C. B. Morton. The letter asked the "Big Three" (General Motors, Ford and Chrysler) to achieve a sales-weighted average of 18.7 m.p.g. on cars produced in the 1980-model year and to move steadily toward that goal between now and then. The figure of 18.7 m.p.g. represents an improvement of about 43 percent over the sales-weighted average of 13.1 m.p.g. for all 1974 models produced by the Big Three. Together GM, Ford and Chrysler accounted for 81 percent of the cars built in that model year. The remaining 19 percent, chiefly imports, averaged 19.8 m.p.g., raising the overall fuel economy on all 1974 cars to 14 m.p.g.

The Government expects that the fuel economy of the cars that averaged 19.8 m.p.g. in 1974 can be raised to 24.7 m.p.g., an improvement of 25 percent. It is assumed that there is less room for improvement in these cars, which are already smaller and lighter than most of the cars built by the Big Three. Thus the goal of 19.6 m.p.g. in the 1980-model year will be achieved if the cars of the Big Three average 18.7 m.p.g. and if all others average 24.7 m.p.g.

The miles-per-gallon figures used in these analyses are for a combined city-highway driving cycle measured on dynamometers by the Environmental Protection Agency (EPA). The figures that one sees in automobile advertisements and on the stickers of new cars show the city and highway fuel economy separately, but roughly speaking the combined cycle is an average of the two. Since the 1974 models built by GM, Ford and Chrysler had different average fuel economies, the percentage increase pledged by each company for its 1980 models varies considerably. GM, which was lowest in 1974 with 12.2 m.p.g., must improve by 53 percent to reach 18.7 m.p.g. Ford must improve only 30 percent (from 14.4 to 18.7) and Chrysler must improve 35 percent (from 13.8 to 18.7).

These percentage improvements look quite different, however, if 1975 models rather than 1974 models are taken as the base year. In 1974 GM improved the average fuel economy of its cars some 28 percent to 15.7 m.p.g., so that it must improve its 1975 models by only 19 percent to reach 18.7 m.p.g. by 1980. Ford,

# Technology: Sputnik, and world peace.

The era of American technological innocence ended abruptly on October 4, 1957 when the Soviet Union launched the first earth satellite, Sputnik I.

The insistent beeping of that 184-pound space package had a traumatic impact on the national psyche. Suddenly the country was forced to concede that it had no monopoly on technical talent, and it began a mobilization of resources to meet the thrust of scientific innovations from other shores. "A man on the moon by 1970," President John F. Kennedy promised, and the realization of that objective helped restore the nation's wounded pride.

But the importance of technological advance in the U.S. and throughout the world far transcends the matter of national pride.

**The implications of technological advance.**

Today technology has become the preferred currency of foreign affairs. It is the bedrock of detente with the Soviet Union, improved relationships with China and our ability to dilute issues in the Middle East. Technological politics is replacing geopolitics. Today nations begin to eye a technological, not a geographical, "heartland."

The significance of these revaluations is that tomorrow's security need not come from mutual fear of MIRVs and ICBMs, but rather from dependence of each country on the other's technological resources as well as natural resources and markets. The advance of technology can help insure that the strategic battles of the future will be fought not with ballistic missiles or bullets, but through economic and technological competition between nations.

**How is the U.S. doing in technology?**

The latest figures compiled by the National Science Board show that the United States is facing much stiffer competition from other nations of the world. Consider these indicators:

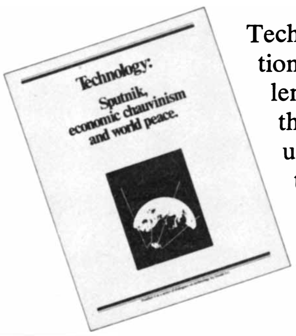
1. The proportion of the gross national product spent for research and development between 1963 and 1971 declined here but increased in the Soviet Union, Japan, and West Germany.
2. After 1967 the Soviet Union surpassed us in the proportion of its population employed in research and development.
3. The rate of growth of patentable ideas with international merit has been expanding at a greater rate in other countries than in the U.S. In fact our "patent balance" fell off 40% between 1966 and 1970.

It is evident that the quantity, if not quality, of U.S. technological leadership is being eroded.

**How can this erosion be stemmed?**

Several steps must be taken. Government must participate more meaningfully in technological innovation. This is not so much a need for government financing as for clearing the path to technological innovation. Government should avoid arbitrary and ill-considered rules, regulations, and standards, and

## We believe in the promise of technology.

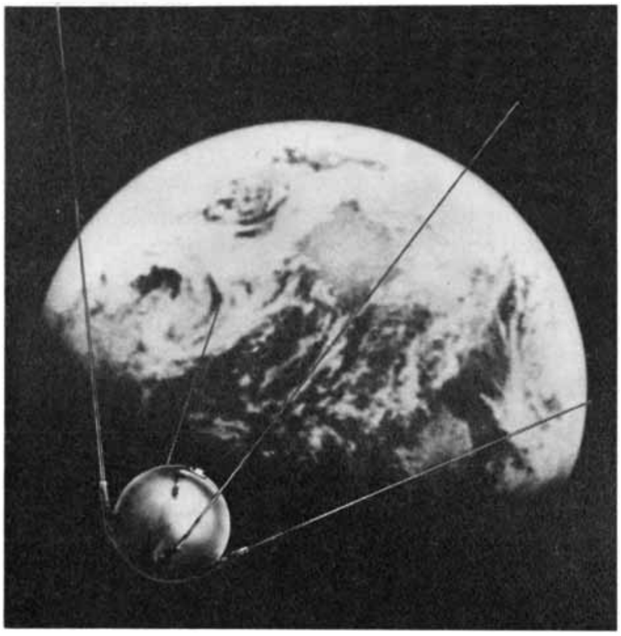



Technology has provided the solutions to many of society's problems. It is also often blamed for them. Some people would have us believe that there's too much technology today – that this very abundance is the basis for so many of our ills.

We believe the solutions to problems lie in the intelligent application of technology—that a misunderstanding of technology's role in man's advancement can only lead to a diminution of his ability to provide solutions.

Therefore, we're sponsoring a series of "white papers" to foster a clearer understanding of technology. Excerpts from the fourth of these papers are published above. If you'd like a copy of the complete text, please write Gould Inc., "Dialogue on Technology," Dept. S-4, 8550 West Bryn Mawr Avenue, Chicago, Illinois 60631.

# economic chauvinism



should establish incentives for new businesses, services, and products.

The understanding and support of labor must be enlisted. Studies show that technology has turned out to be the working man's best friend. It has enabled him to increase his productivity, and therefore his income.

The multinational corporation must be viewed as an asset, not as a drain on the economy. Data shows that overseas plants have a decided "pull effect." They become markets themselves for numerous ancillary products and components made domestically.

Finally, to maintain its domestic base, every company must advance its own technology to bring forth new products, services, and businesses.

**Progress, yes. Secrecy, no.**
The value of technology and science on the international scene does *not* imply the hoarding of discoveries and inventions. There is much to learn from others in the world. There were foreign, not only U.S., contributions to such developments as the videotape recorder, the electron microscope, magnetic ferrite memories, and the birth control pill.

Science and technology are truly international endeavors, and knowledge becomes an ever-easier commodity to transport in this modern day of easy communication and population mobility.

**Economic chauvinism must be rejected.**
No future U.S. president is likely to ask, even in the privacy of the Oval Office, "Why should we be concerned with the lira?" or the pound, mark, or yen. The challenge for the U.S. is to direct its technological and economic strategies not toward "beating" one country or another, but toward building a world where nations "do their thing" in exchange for what other nations can supply in return.

A growing emphasis on civilian technology offers the hope that balance-of-power relationships based on military strength will be supplanted in time with what the late industrialist Thomas J. Watson, Sr. called, "World peace through world trade." Achieving the goal depends on inventions, new products, services, processes, and marketing skills.

**Science and technology can solve many problems.**
**If they don't, what else will?**

**GOULD**
**the proud inventors**

on the other hand, dropped about 8 percent in fuel economy in 1975 (to 13.3 m.p.g.) and hence must show an improvement of about 40 percent to reach the 1980 goal. For Chrysler, which showed an improvement of 15 percent between 1974 and 1975, the net remaining improvement comes to about 18 percent, or slightly less than the improvement needed by GM.

The recommendation of using 1974 models as the base year was made jointly by the Department of Transportation and the EPA in its report to Congress last October "Potential for Motor Vehicle Fuel Economy Improvement"). The report concluded that a 40 percent improvement was readily attainable and that if the buying public could be encouraged to switch to smaller cars, the average fuel economy in 1980 might even reach 22.2 m.p.g., an improvement of nearly 60 percent over 1974 (see "The Fuel Consumption of Automobiles," by John R. Pierce; SCIENTIFIC AMERICAN, January). There is considerable sentiment in Congress for making improvements in fuel economy mandatory rather than voluntary.

## *Lysosomal Medicine*

The techniques of molecular biology have uncovered a large class of diseases caused by enzyme deficiencies. They are hereditary diseases; people who inherit an anomalous gene from both parents lack a particular enzyme or have an inactive form of the enzyme. A surprising number of these diseases have been traced to enzymes found in the organelle called the lysosome. More than 30 have been identified so far, including Tay-Sachs disease, Niemann-Pick disease and Hunter-Hurler syndrome.

The lysosomes are small sacs of degradative enzymes found in almost all cells. Christian de Duve, who discovered the organelle in 1955 (and who last year was awarded a Nobel prize for his discovery), has explained its function as that of the digestive tract of the cell. It engulfs foreign matter such as bacteria and outworn components of the cell, recovers useful constituent molecules and discharges the waste. The material to be eliminated is enveloped in a membrane in a process called endocytosis and is then broken down by the lysosomal enzymes. In the lysosomal diseases the last function is impaired; in most cases the symptoms of the illness are produced by the accumulation of the substrates of the missing enzyme. The result is a kind of cellular constipation.

It has long been suspected that the symptoms of the lysosomal diseases could be alleviated if the needed enzyme could be got into the lysosome. Simply injecting the enzyme into the body is ineffective: the molecules are quickly labeled by the immune system and destroyed. A recently devised technique employs just this immunological capability to "fool" the cell into accepting the enzyme.

The method was developed by Gerald Weissmann of the New York University School of Medicine, working with six students at the Marine Biological Laboratory in Woods Hole, Mass.: David Bloomgarden, Roberta Kaplan, Charles Cohen, Tucker Collins, Avrum Gotlieb and David Nagle; also participating was Sylvia Hoffstein. The project was undertaken as a class experiment during a summer course at Woods Hole; it is described in *Proceedings of the National Academy of Sciences.*

The enzyme employed by Weissmann and his co-workers was a peroxidase, one of the group of enzymes that participate in the lysosomal destruction of bacteria. It was introduced into cultures of cells taken from the smooth dogfish, a primitive fish related to the sharks. The cells were phagocytes resembling some of the cells of the mammalian immune system.

The enzyme was enclosed in a package called a liposome, which is made up of membranes similar in composition to those that surround the cell and the lysosome itself. The membranes consist of phospholipids, substances that in certain solutions spontaneously form membranous structures. In the liposome the membranes are organized in tight, globular masses many layers thick. The enzyme is trapped in water-filled spaces between the layers.

Liposomes containing enzymes were first prepared in 1970 by Grazia Sessa and Weissmann. The innovation introduced in Weissmann's recent experiment was a method of inducing the cell to actively take up the liposomes. This was accomplished by coating the liposomes with dogfish immunoglobulins, or antibodies. When the immunoglobulins were aggregated by heat treatment, the liposomes seemed to the phagocytes like foreign particles, such as bacteria, against which an immune response had been mounted. As a result the liposome, with its freight of enzyme, was taken into the cell and the lysosome by endocytosis.

Weissmann and his co-workers found that about half of the enzyme administered by this method entered the lysosomes. In comparison, when the free enzyme was merely added to the cell culture, only about 1 percent of it reached the lysosomes.

## *Cosmographicum Mysterium*

One of the most puzzling problems in contemporary astrophysics is the result of a little-known accidental discovery. As a result of the Partial Test-Ban Treaty of 1963, which prohibited nuclear explosions in space, the U.S. launched five satellites of the *Vela* series to act as monitors. Each satellite was equipped with a detector that was designed to respond to gamma rays from a nuclear explosion; the relative times at which the detectors aboard two or more satellites responded could be used to determine the position of the gamma-ray source. When the records from the satellites were examined, it was found that the detectors had been triggered by occasional bursts of gamma rays—but that the source of the bursts could not possibly be anything in the vicinity of the earth.

Each burst lasts for about 10 seconds and does not seem to recur. The spectra of the bursts are quite similar to one another and show rapid small-scale fluctuations, implying that the sources must be very small, perhaps objects no larger than the earth. An average of four bursts per year have been detected since the first was detected in 1967. The sources appear to be distributed randomly over the sky.

Theories about the nature of the bursts have proliferated. At first an attempt was made to see if the gamma-ray bursts were associated with known objects, particularly the most peculiar ones. Perhaps the gamma rays were produced in the early stages of the events that gave rise to the radio outbursts of quasars. Or perhaps they originated in the shock waves from supernovas in other galaxies. Or they were associated with flare stars or X-ray sources within our own galaxy. In favor of the last possibility is the fact that one of the bursts observed in 1972 originated in approximately the same direction as the well-known X-ray source Cygnus X-1 and at about the same time that the spectrum of that source changed abruptly. One such coincidence, however, is not compelling evidence, and many other X-ray sources apparently do not emit gamma rays.

There are even more exotic theoretical possibilities to choose from. Some of them involve "glitches" in the crystal structure of the crust of a neutron star. The glitches could be caused by "starquakes"; such quakes could result either from spontaneous changes within the

# DP SCIENCE DIALOG

Notes and observations from IBM which may prove of interest to the scientific and engineering communities.

*Dr. G. William Cole (left), Dr. David R. Kelly and Mrs. Debbie Green in the hospital laboratories at the Medical Center of the University of Alabama in Birmingham. The display terminal is an IBM 3270 through which blood test results are entered in the computer.*

## Making Medical Judgments With Computer Aid

For certain kinds of illness, laboratory tests are an effective way to establish a diagnosis. It is not always easy, though, to decide which tests to perform and in what order—which can mean delay in identifying the problems. A computer-based system now under development is proving useful in aiding doctors both in the detection and confirmation of such clinical problems.

At the University Hospital, part of the Medical Center of the University of Alabama in Birmingham, a computer compares the results of tests given to patients on admission to the hospital with a computer-stored profile of results of the same tests for a data base of thousands of patients. Test results for incoming patients are entered in the computer, a System/370 Model 125 used by the university hospitals, through several IBM terminals.

Taking the individual test results, the computer calculates probabilities that certain clinical problems exist in the patient. By following branching logic (a "decision tree"), it is possible to decide what further testing is required to lead to a definitive diagnosis.

For example, anemia due to iron depletion can be detected or confirmed and the probability of clinical correlation determined if the patient's blood is tested for hemoglobin content, serum iron content and average red cell size (mean corpuscular volume). Should all three measurements be within certain limits, the diagnosis of iron depletion can be excluded.

But if any of the values are reduced below the "normal" range, an additional test, serum transferrin or iron-binding protein, is performed to deter-

*(Continued on third page)*

# Cryogenics: An Advanced Technology For Computing

Just as semiconductors revolutionized computing circuitry in the past 20 years, advanced technology involving cryogenics—reducing temperatures to very low levels approaching absolute zero—may bring far greater speed to computing in the future.

A completely new type of switch that forms the basis of new logic and memory circuits is being developed by scientists at IBM's Thomas J. Watson Research Center in Yorktown Heights, New York and at IBM's Research Laboratory in Zurich, Switzerland.

The advanced nature of this work is illustrated by the speed of the switch. It can operate at about ten trillionths of a second—more than 100 times faster than the fastest transistor now used in computers. Equally important, the switch requires only one ten-thousandth the power needed to run present day transistors, thus significantly reducing the amount of heat generated.

Simultaneously increasing speed *and* reducing heat is not easy to accomplish. Dr. Wilhelm Anacker of the Yorktown Research Center explains why: "To make ordinary transistors switch at top speed, they must be driven by high current which increases the amount of heat generated. And to speed the transmission of signals between them, the transistors must be placed very close together. Both these conditions sharply increase the risk of overheating."

In contrast, the new switches show promise of alleviating the overheating problem, while greatly increasing the switching speed. They are based on the theoretical work of British Nobel Laureate Brian Josephson. Over a decade ago, he predicted what is now known as the "Josephson Effect." In this phenomenon, electron pairs can tunnel through very thin, normally impenetrable insulators, when sandwiched between superconducting metal strips. Superconductivity is the state in which materials lose all electrical resistance when they are cooled to temperatures approaching absolute zero (−460°F).

In Josephson tunneling, current can pass through the insulator with no voltage drop if current flow is kept below a certain threshold. Application of a small magnetic field can reduce the threshold, causing a very small voltage drop to appear across the insulator.

Using those two facts, IBM Research scientist, Dr. Juri Matisoo was the first to construct a high-speed device that can be switched between a "voltage" and "no voltage" state. The switch forms the basic circuit element in the new technology.

By building an adder, shift register and memory cells using this technology, IBM scientists have demonstrated the feasibility of constructing computer circuits using Josephson devices. The memory cell, for example, consists of a superconducting ring in which a superconducting current can be made to circulate—indefinitely and without power—in either a clockwise or counterclockwise direction. This provides a way to represent the "zeros" and "ones" of computer language. The direction of the current flow can be reversed in less than 100 trillionths of a second. A rudimentary adder has been built that consists of five interconnecting logic cir-

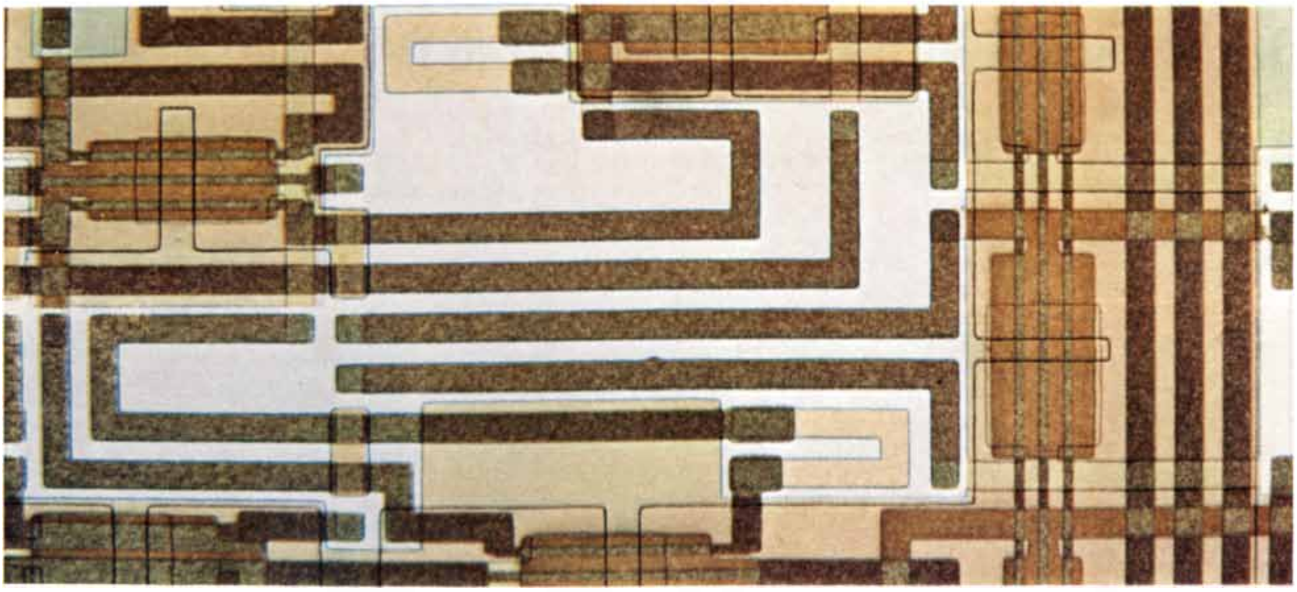
*After high-energy deuteron bombardment, a radioactive magnesium target is handled inside a "hot" cell at NEN's North Billerica, Mass. facility.*

# Computers Help Make NASA Data Available To Public

"What is the most effective method of electroplating magnesium onto copper in order to produce Sodium 22 ($^{22}Na$)?"

NASA—the National Aeronautics and Space Administration—might have researched that very process at some time in learning to fly men to the moon. The Space Act of 1958, which created NASA, required that its technological discoveries be made available to the public. As a result, non-restricted NASA data has been entered into computers at six non-profit industrial applications centers across the country.

One of them, part of the University of Connecticut at Storrs, is the New England Research Application Center (NERAC), established in 1966. In addition to NASA material, the center's IBM System/370 Model 115 computer also stores data gathered by numerous technical societies, adding some 100,000 new items each month. A staff of specialists in various fields of science and engineering responds to requests, which are accepted from fee-paying



*Photomicrograph of a one-bit adder in which switching is done by recently developed devices called Josephson junctions.*

cuits, which has been able to add two single bits of information in as little as 500 trillionths of a second.

The superconducting circuitry is kept cold by immersion in a liquid helium bath held in a cryostat—a container resembling a thermos bottle.

Dr. Anacker reports that Josephson junction technology is still in an early stage of development with many more improvements necessary before the new circuitry could ever be made commercially. He adds: "After observing experimentally that rudimentary switches, adders, memory cells and shift registers work well, the use of Josephson technology in computers of the future is now an exciting possibility."

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*Inside a "hot" cell, $^{22}$Na in solution is transferred to a teflon vessel before evaporation.*

industrial clients and from state and local governments.

For example, a specialist in engineering discussed the question quoted above with the client, New England Nuclear Corporation of North Billerica, Massachusetts, a manufacturer of radioactive chemicals and pharmaceuticals. Then he worked out a retrieval strategy involving a search of two million items in the NERAC files. In total, the computer ran two major searches and retrieved two relevant documents, one from NASA research and the other from the American Society of Metals.

The specialist then forwarded the desired documents to New England Nuclear. The NASA data provided precisely the information the company needed in order to begin producing $^{22}$Na. This is a radioactive isotope used as a tracer in circulatory and extracellular fluid studies vital in medical and biological research.

"NERAC's service saved us at least two weeks of library research and even then there's no guarantee we would have located the right article. We are currently one of the few American companies producing $^{22}$Na in significant commercial quantities," says Gregory Rocco, manager of Nuclides and Sources Division of New England Nuclear.

Virtual storage and multiprogramming on the Model 115 have made possible enlarged and expedited data searches, according to Dr. Daniel Wilde, director of NERAC. "We can be doing a search for one company and simultaneously be updating the data base, editing, and printing results for other clients.

"We encourage our clients to ask as many questions as possible, so if one approach fails, another might be productive," says Dr. Wilde. "This is feasible because the Model 115 is dedicated to this application and we take full advantage of its advanced capabilities."

# Medical Judgments...

*(Continued from first page)*

mine the percentage of iron bound to transferrin. Again, the computer compares this value with the data base results for this test. The comparison either adds to the probability of iron depletion anemia or detracts from it. If the probability is increased, further measures can lead to a definite diagnosis. If it is decreased, another branching of the "decision tree" may be followed that leads to alternative diagnoses.

"By developing these test systems and the test organizational pattern, it is possible to provide the clinician with efficient guides to clinical problem identification," says Dr. G. William Cole, Professor of Clinical Pathology of the Medical School of the University of Alabama in Birmingham. "The quantitative values produced by this method serve as much better definitions of probability than such terms as 'occasionally,' 'usually,' 'once in a while' which clinicians may be forced to use to sum up frequency of occurrence.

"What the computer system does, of course," he adds, "is simply to produce numerical values of probability based on wide experience with selected criteria. Qualitative judgments, such as clinical decisions and diagnoses remain, as always, the province of the clinician."

*Advertisement*

# Interactive Computing at Pratt & Whitney Aircraft

Two engineers, seated at a computer terminal, intently study the diagram of a turbine fan blade displayed on the lighted screen.

"Let's rotate the blade ten degrees," says one. The other touches a pen-like device to the screen and pushes a button on the terminal's control panel. The graphic display on the screen goes dark and then brightens again with the contours of the diagram somewhat altered. "That's better," they agree. More changes follow on the screen until the engineers are satisfied they have achieved the most effective design.

Interactive computing is the order of the day at the engineering facility of the Pratt & Whitney Aircraft Division of United Aircraft. In the instance cited, the component being designed was a cooling tube to be fitted inside the turbine blades of an advanced turbofan engine.

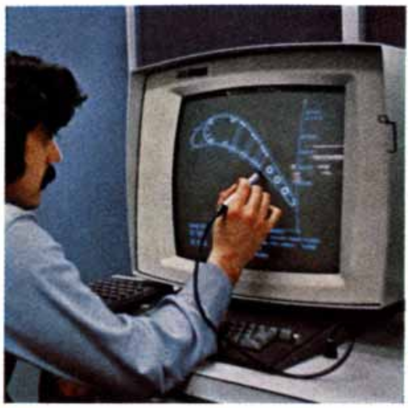
"The interactive method greatly increases the efficiency of the engineer," says Dr. Edwin N. Nilson, manager of technical and management data systems for Pratt & Whitney Aircraft engineering. "Under the batch method, it used to take as much as two weeks to complete a particular segment of a design. Now it takes two days. Design lead times of critical engine parts have been reduced by as much as 50 percent. We can produce several alternatives and select the best one in the same time it used to take to prepare one design. Better computer simulations mean that final designs are increasingly long-lived."

At Pratt & Whitney Aircraft's East Hartford, Connecticut plant, computer-aided design is coupled with computer-aided manufacturing. The two methods utilize a massive shared data base linking design, drafting and manufacturing.

For instance, the design of a component, once generated and stored in the computer, is ready for any subsequent changes. The design can be modified in accordance with performance test results, which are also stored in the computer. It can be produced as an engineering drawing through a computer-based automated drafting facility.

And following final approval, the computer makes the design specifications swiftly available to production engineers. Numerical control programs can thereby be developed that can both produce dies and control machine tools on the factory floor.

In short, Pratt & Whitney Aircraft is putting interactive computing to work in a comprehensive systems approach to jet engine design and manufacture.



*An engineer modifies the design of a turbine blade and cooling tube using an IBM graphics terminal.*


*Engines in production at Pratt & Whitney Aircraft.*

Interactive graphics at Pratt & Whitney Aircraft runs under IBM's Conversational Monitor System. The host computer is a System/370 Model 168, operating under Virtual Machine/370 programming, and is situated in the engineering department. Linked to it are 59 interactive terminals for scientific and engineering use. Engineering also employs a second Model 168 for batch use and data communications work.

As Theodore Slaiby, manager of design and analysis puts it, "Our interactive capability allows our design engineers to concentrate on doing what they do best, which is creating. We can see the results in far greater productivity for engineering as a whole."

*DP Science Dialog is concerned with topics which may prove of interest to the scientific and engineering communities. Your comments and suggestions are welcome. Just write: Editor, DP Science Dialog, IBM Data Processing Division, 1133 Westchester Ave., White Plains, N.Y. 10604.*

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star's crust or from matter falling onto the crust and somehow fracturing it. Depending on the particular hypothesis, the falling matter could be anything from gas thrown off by a companion star to the nucleus of a comet drawn in by the neutron star's gravitation.

Another hypothesis posits that chunks of antimatter occasionally collide with a star, and that the mutual annihilation of some of the star's matter and the antimatter yields the gamma rays. It has also been proposed that there are tiny black holes left over from the formation of the universe that are slowly evaporating; at the end of their life they emit huge amounts of energy, some of which is in the form of gamma rays. Closer to home is the suggestion that an occasional grain of interstellar dust, approaching the solar system at nearly the speed of light, encounters photons moving outward from the sun and generates a burst of gamma rays by fluorescence. In a recent article in *The New Scientist* Andrew Fabian and James Pringle of the University of Cambridge remark: "Let us... hope that the rate of discovery of new bursts exceeds the rate of production of new theories."

## *Good Juice*

The traditional procedure for harvesting a forage crop such as alfalfa usually entails making three trips through the field: one to cut the crop, one (sometimes bypassed) to rake it so that it will dry more thoroughly and one to pick it up. The procedure results in certain losses; for example, as much as 20 percent of the dried leaf and small-stem material, which is the most nutritious part of the plant, can shatter and fall to the ground. The proteins and amino acids of forage crops are not fully utilized in another sense: since such crops can be digested only by ruminants, the nutrients in them are not directly available to other animals, including man. In an effort to exploit the full potential of forage crops an interdisciplinary group at the University of Wisconsin has developed a program for extracting proteins and amino acids from such plants in the form of juice, producing a concentrate that is suitable for a wide range of animals and leaving a solid residue that is still nutritious for ruminants.

In the Wisconsin method the crop is harvested in a single pass through the field and then put into a machine that separates the juice from the fiber. The concentrate can be sold off the farm as high-protein feed, a food or a food additive, and the residue can be dried or put into a silo. Indeed, according to Neal Jorgensen, a dairy-science specialist with the program, the process "enhances silage production," because after the extraction of juice "the remaining nutrients in the plant fibers are readily exposed to fermentation bacteria and enzymes" and fermentation is faster than in conventional ensiling.

The Wisconsin workers tried their process on a number of crops and found that alfalfa yields the most protein per acre. Mark A. Stahmann, a biochemist with the program, wrote: "Fresh-cut alfalfa contains about 21 percent protein and 23 percent fiber. With our small machine we extracted 43 percent of the protein. This was spray-dried to form a green powder containing 35 percent protein, .7 percent fiber and about 40 percent nitrogen-free extract, largely carbohydrates. The residue contained 16 percent protein and 33 percent fiber. The spray-dried alfalfa juice contained 16 times more thiamine than dehydrated alfalfa, about twice as much riboflavin, three times more carotene and 3½ times more xanthophyll."

The Wisconsin group is also interested in extracting protein from vegetable wastes such as beet tops, carrot tops, bean plants and potato vines. Stahmann has estimated that some 21 million tons of these wastes, containing 393,000 tons of protein, are lost in the U.S. annually. Protein extracted from such sources, he says, could be made into nutritious concentrates for animals and "might be converted into food for humans as is now done with soybean meal."

## *The Artificial Lung*

The artificial lung may soon join the list of dependable man-made temporary replacements for malfunctioning human organs. It is still in an experimental stage and far from being available for routine treatment, but in the past seven years it has saved some patients suffering from acute respiratory failure; it can take over the function of the lungs for much longer periods than the heart-lung machines developed in the 1950's. Now a major test of the artificial lung is under way in nine centers established during the past year in a three-year collaborative program sponsored by the National Heart and Lung Institute.

What the human lung does, of course, is exchange gases: oxygen and carbon dioxide. Blood flows through fine capillaries wrapped around 300 million tiny sacs, the alveoli, into which inspired air is drawn. Molecules of gas diffuse across the thin membrane consisting of the walls of the alveoli and the capillaries in the direction of the concentration gradient. There is more oxygen in the air than in the deoxygenated hemoglobin of the venous blood, and so oxygen molecules diffuse from the air to the blood; conversely, carbon dioxide is more concentrated in the blood and so it diffuses in the opposite direction. In the artificial lung, or membrane oxygenator, the same result is achieved, albeit less efficiently. A silicone-rubber membrane is substituted for the alveolar and capillary tissue; oxygen moves over one side of the membrane and venous blood over the other side, and the gases are exchanged. In a version developed in 1962 by Theodor Kolobow of the Heart and Lung Institute the membrane is shaped into a flat sleeve that is wrapped repeatedly around a spool. Oxygen is aspirated through the sleeve, and blood from a large vein of the patient is circulated in the spaces between the layers of the coiled sleeve.

The thinnest practicable rubber membrane is far thicker than the natural one and its total surface is only some five square meters as compared with the human lung's 75 square meters of gas-exchange surface. Moreover, the blood layer is so relatively thick that a stagnant layer develops along the membrane, further reducing gas exchange. As a result most artificial lungs can transfer only about 250 milliliters of oxygen per minute, which is the normal requirement for a resting adult.

Acute respiratory failure can result from a wide variety of diseases and conditions including pulmonary embolism, pneumonia, direct injury to the lung and a "shock lung" syndrome that sometimes follows massive trauma. The function of the artificial lung is to take over part or even all of the gas-exchange function until the natural lung recovers. To date some 150 patients in the advanced stages of acute respiratory failure have been supported on the artificial lung for up to three weeks; about 15 percent of the patients eventually recovered. The therapy should be applied in far more cases and should be instituted earlier, according to Warren M. Zapol of the Massachusetts General Hospital, one of the leaders in developing the membrane oxygenator. The objective of the new investigative program organized by the Heart and Lung Institute is to accumulate a large number of cases under standard conditions and criteria of success in order to evaluate the effectiveness of the artificial lung as compared with conventional treatments.

# DINOSAUR RENAISSANCE

## The dinosaurs were not obsolescent reptiles but were a novel group of "warm-blooded" animals. And the birds are their descendants

by Robert T. Bakker

The dinosaur is for most people the epitome of extinctness, the prototype of an animal so maladapted to a changing environment that it dies out, leaving fossils but no descendants. Dinosaurs have a bad public image as symbols of obsolescence and hulking inefficiency; in political cartoons they are know-nothing conservatives that plod through miasmic swamps to inevitable extinction. Most contemporary paleontologists have had little interest in dinosaurs; the creatures were an evolutionary novelty, to be sure, and some were very big, but they did not appear to merit much serious study because they did not seem to go anywhere: no modern vertebrate groups were descended from them.

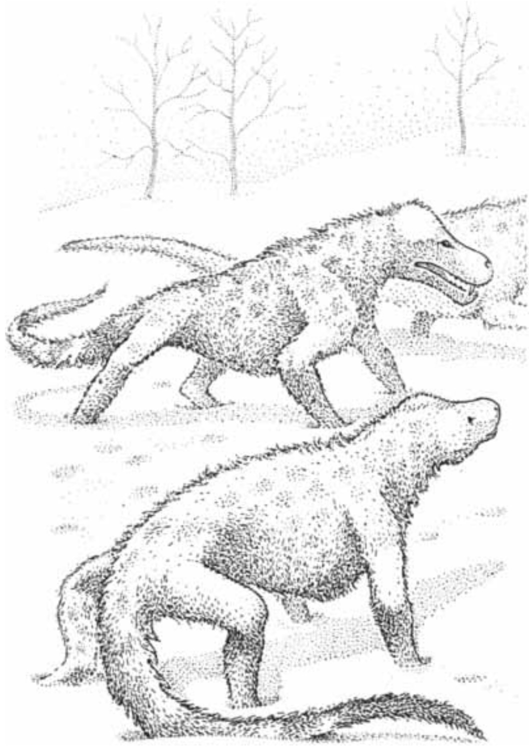
Recent research is rewriting the dinosaur dossier. It appears that they were more interesting creatures, better adapted to a wide range of environments and immensely more sophisticated in their bioenergetic machinery than had been thought. In this article I shall be presenting some of the evidence that has led to reevaluation of the dinosaurs' role in animal evolution. The evidence suggests, in fact, that the dinosaurs never died out completely. One group still lives. We call them birds.

### Ectothermy and Endothermy

Dinosaurs are usually portrayed as "cold-blooded" animals, with a physiology like that of living lizards or crocodiles. Modern land ecosystems clearly show that in large animals "cold-bloodedness" (ectothermy) is competitively inferior to "warm-bloodedness" (endothermy), the bioenergetic system of birds and mammals. Small reptiles and amphibians are common and diverse, particularly in the Tropics, but in nearly all habitats the overwhelming majority of land vertebrates with an adult weight of 10 kilograms or more are endothermic birds and mammals. Why?

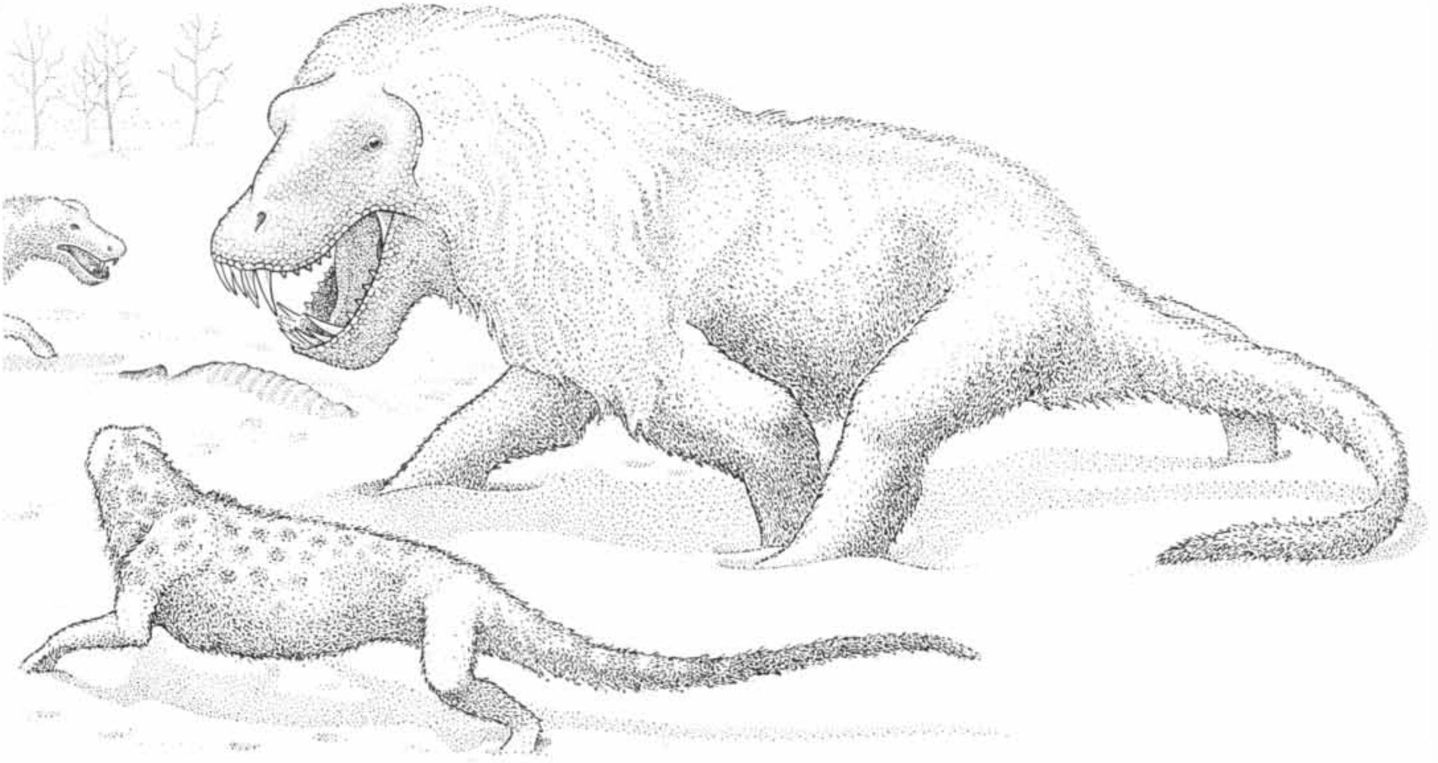
The term "cold-bloodedness" is a bit misleading: on a sunny day a lizard's body temperature may be higher than a man's. The key distinction between ectothermy and endothermy is the rate of body-heat production and long-term temperature stability. The resting metabolic heat production of living reptiles is too low to affect body temperature significantly in most situations, and reptiles of today must use external heat sources to raise their body temperature above the air temperature—which is why they bask in the sun or on warm rocks. Once big lizards, big crocodiles or turtles in a warm climate achieve a high body temperature they can maintain it for days because large size retards heat loss, but they are still vulnerable to sudden heat drain during cloudy weather or cool nights or after a rainstorm, and so they cannot match the performance of endothermic birds and mammals.

The key to avian and mammalian endothermy is high basal metabolism: the level of heat-producing chemical activity in each cell is about four times higher in an endotherm than in an ectotherm of the same weight at the same body temperature. Additional heat is produced as it is needed, by shivering and some other special forms of thermogenesis. Except for some large tropical endotherms (elephants and ostriches, for example), birds and mammals also have a layer of hair or feathers that cuts the rate of thermal loss. By adopting high heat production and insulation endotherms have purchased the ability to maintain more nearly constant high body temperatures than their ectothermic competitors can. A guarantee of high, constant body temperature is a powerful adaptation because the rate of work output from muscle tissue, heart and lungs is greater at

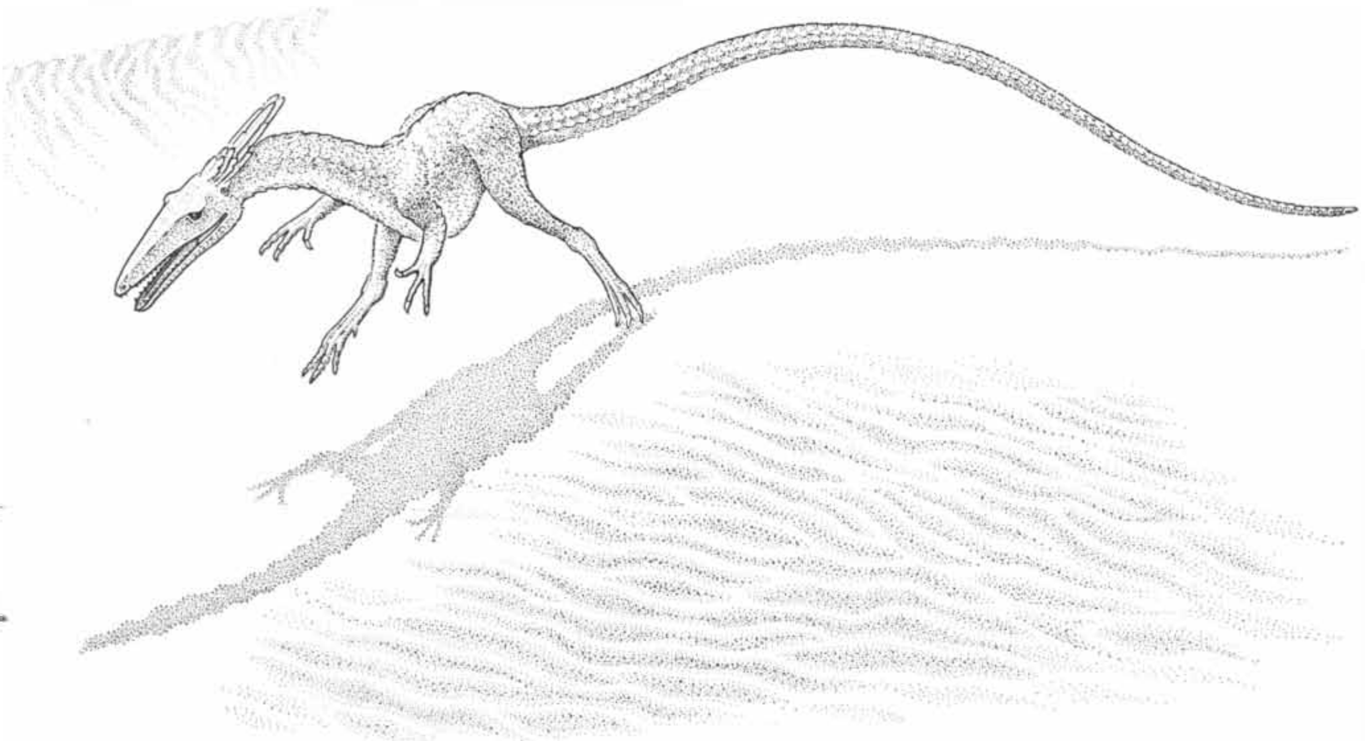


**HAIRY THERAPSIDS, mammal-like reptiles of the late Permian period some 250 million years ago, confront one another in the snows of southern Gondwanaland, at a site that is now in South Africa.** ***Anteosau-***

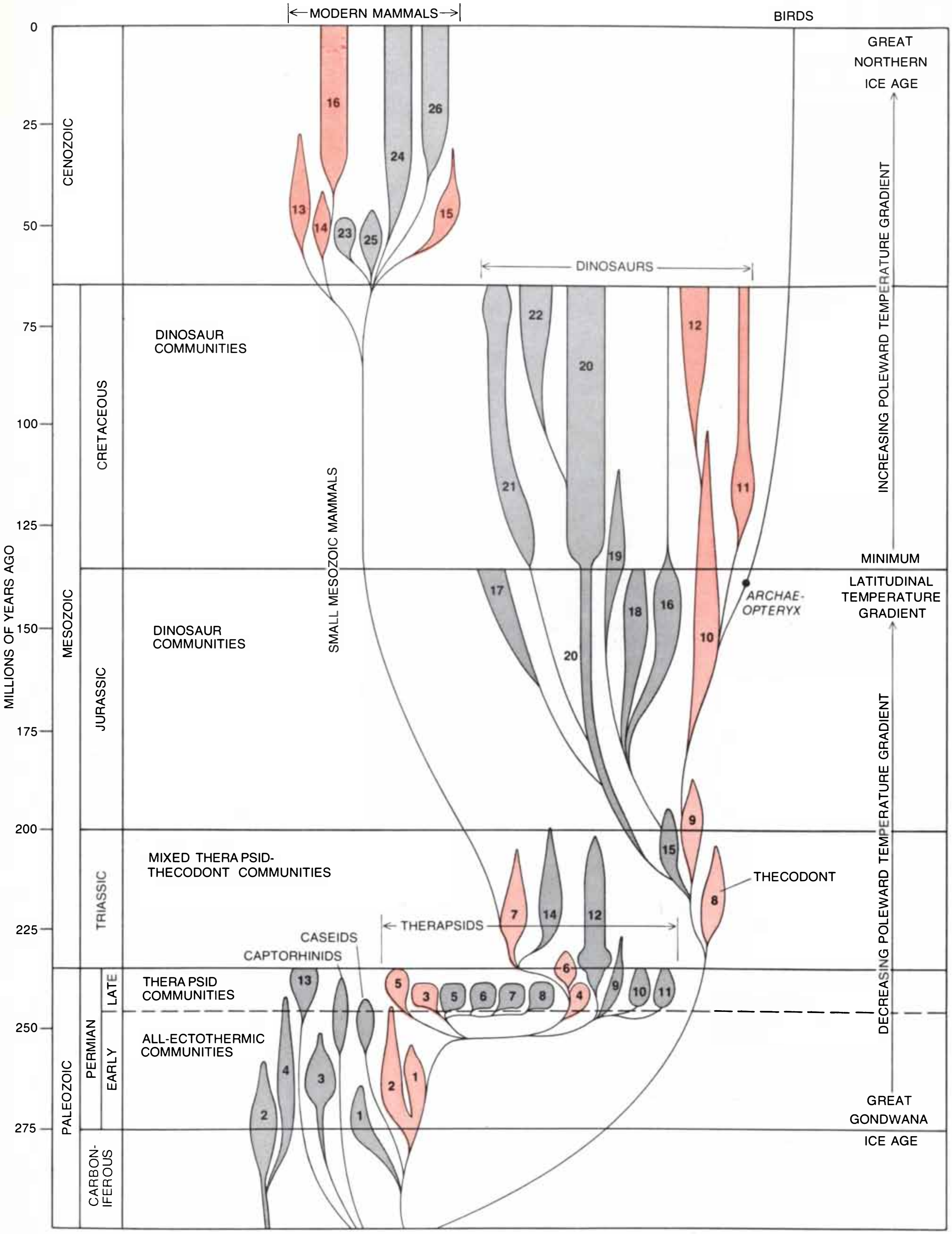
**FEATHERED DINOSAUR,** ***Syntarsus,*** **pursues a gliding lizard across the sand dunes of Rhodesia in the early Jurassic period some 180 million years ago. This small dino-**



*rus* (*right*), weighing about 600 kilograms, had bony ridges on the snout and brow for head-to-head contact in sexual or territorial behavior. Pristerognathids (*left*) weighed about 50 kilograms and represent a group that included the direct ancestors of mammals. The reconstructions were made by the author on the basis of fossils and the knowledge, from several kinds of data, that therapsids were endothermic, or "warm-blooded"; those adapted to cold would have had hairy insulation. The advent of endothermy, competitively superior to the ectothermy ("cold-bloodedness") of typical reptiles, is the basis of author's new classification of land vertebrates.



saur (adult weight about 30 kilograms) and others were restored by Michael Raath of the Queen Victoria Museum in Rhodesia and the author on the basis of evidence that some thecodonts, ancestors of the dinosaurs, had insulation and on the basis of close anatomical similarities between dinosaurs and early birds. Dinosaurs, it appears, were endothermic, and the smaller species required insulation. Feathers would have conserved metabolic heat in cold environments and reflected the heat of the sun in hot climates such as this.

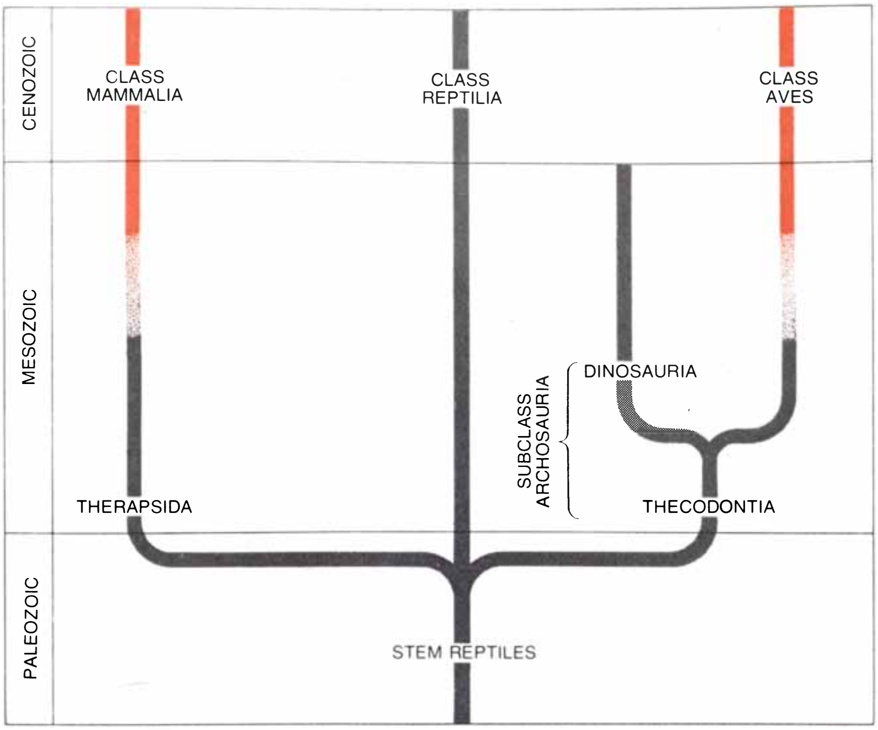



**PREDATOR-PREY SYSTEMS** of land vertebrates and the paths of descent of successive groups are diagrammed with the predators (*color*) and the prey animals (*gray*) numbered to refer to the groups named and pictured in the illustrations on pages 64 through 67. The relative importance of the live biomass represented by fossils is indicated by the width of the gray and colored pathways.

high temperatures than at low temperatures, and the endothermic animal's biochemistry can be finely tuned to operate within a narrow thermal range.

The adaptation carries a large bioenergetic price, however. The total energy budget per year of a population of endothermic birds or mammals is from 10 to 30 times higher than the energy budget of an ectothermic population of the same size and adult body weight. The price is nonetheless justified. Mammals and birds have been the dominant large and medium-sized land vertebrates for 60 million years in nearly all habitats.

In view of the advantage of endothermy the remarkable success of the dinosaurs seems puzzling. The first land-vertebrate communities, in the Carboniferous and early Permian periods, were composed of reptiles and amphibians generally considered to be primitive and ectothermic. Replacing this first ectothermic dynasty were the mammal-like reptiles (therapsids), which eventually produced the first true mammals near the end of the next period, the Triassic, about when the dinosaurs were originating. One might expect that mammals would have taken over the land-vertebrate communities immediately, but they did not. From their appearance in the Triassic until the end of the Cretaceous, a span of 140 million years, mammals remained small and inconspicuous while all the ecological roles of large terrestrial herbivores and carnivores were monopolized by dinosaurs; mammals did not begin to radiate and produce large species until after the dinosaurs had already become extinct at the end of the Cretaceous. One is forced to conclude that dinosaurs were competitively superior to mammals as large land vertebrates. And that would be baffling if dinosaurs were "cold-blooded." Perhaps they were not.



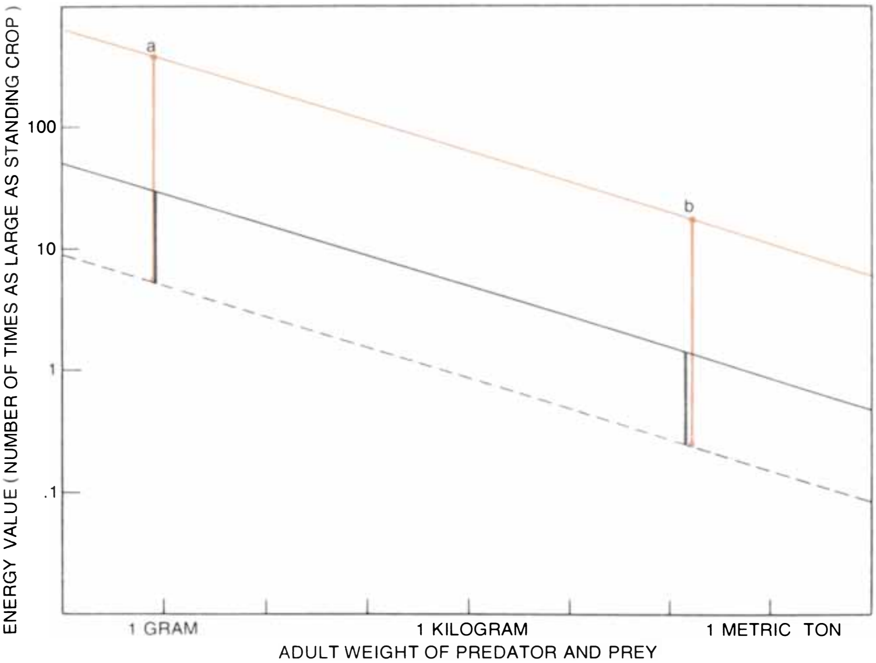

**USUAL CLASSIFICATION of land vertebrates (excluding the Amphibia) is diagrammed here in a highly simplified form. The classes are all descended from the original stem reptiles. Birds (class Aves) were considered descendants of early thecodonts, not of dinosaurs, and endothermy (*color*) was thought to have appeared gradually, late in the development of mammals and birds. The author proposes a reclassification (*see illustration on page 77*).**

### Measuring Fossil Metabolism

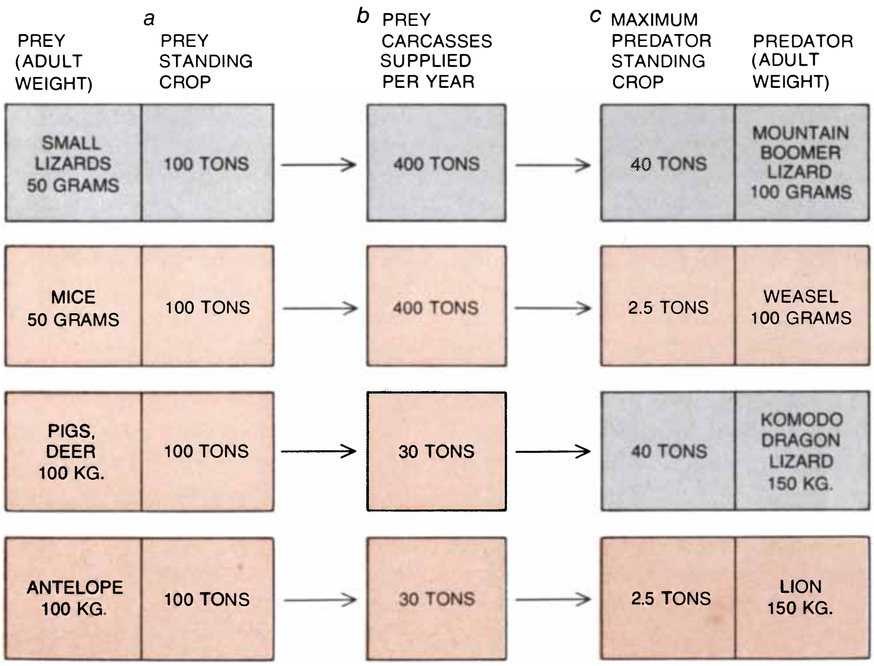
In order to rethink traditional ideas about Permian and Mesozoic vertebrates one needs bioenergetic data for dinosaurs, therapsids and early mammals. How does one measure a fossil animal's metabolism? Surprising as it may seem, recent research provides three independent methods of extracting quantitative metabolic information from the fossil record. The first is bone histology. Bone is an active tissue that contributes to the formation of blood cells and participates in maintaining the calcium-phosphate balance, vital to the proper functioning of muscles and nerves. The low rate of energy flow in ectotherms places little demand on the bone compartment of the blood and calcium-phosphate system, and so the compact bone of living reptiles has a characteristic "low activity" pattern: a low density of blood vessels and few Haversian canals, which are the site of rapid calcium-phosphate exchange. Moreover, in strongly seasonal climates, where drought or winter cold forces ectotherms to become dormant, growth rings appear in the outer layers of compact bone, much like the rings in the wood of trees in similar environments. The endothermic bone of birds and mammals is dramatically different. It almost never shows growth rings, even in severe climates, and it is rich in blood vessels and frequently in Haversian canals. Fossilization often faithfully preserves the structure of bone, even in specimens 300 million years old; thus it provides one window through which to look back at the physiology of ancient animals.

The second analytic tool of paleobioenergetics is latitudinal zonation. The present continental masses have floated across the surface of the globe on lithospheric rafts, sometimes colliding and pushing up mountain ranges, sometimes pulling apart along rift zones such as those of the mid-Atlantic or East Africa. Paleomagnetic data make it possible to reconstruct the ancient positions of the continents to within about five degrees of latitude, and sedimentary indicators such as glacial beds and salt deposits show the severity of the latitudinal temperature gradient from the Equator to the poles in past epochs. Given the latitude and the gradient, one can plot temperature zones, and such zones should separate endotherms from ectotherms. Large reptiles with a lizardlike physiology cannot survive cool winters because they cannot warm up to an optimal body temperature during the short winter day and they are too large to find safe hiding places for winter hibernation. That is why small lizards are found today as far north as Alberta, where they hibernate underground during the winter, but crocodiles and big lizards do not get much farther north than the northern coast of the Gulf of Mexico.

The third meter of heat production in extinct vertebrates is the predator-prey ratio: the relation of the "standing crop" of a predatory animal to that of its prey. The ratio is a constant that is a characteristic of the metabolism of the predator, regardless of the body size of the animals of the predator-prey system. The reason-




**PREDATOR-PREY RATIO** remains about constant regardless of the size of the animals involved because of the scaling relations in predator-prey energy flow. The yearly energy budget, or the amount of meat required per year per kilogram of predator, decreases with increasing weight for endotherms (*colored curve*) and for ectotherms (*solid black curve*). The energy value of carcasses provided per kilogram by a prey population decreases with increasing weight at the same rate (*broken black curve*). The vertical lines are proportional to the size of the prey "standing crop" required to support one unit of predator standing crop: about an order of magnitude greater for endothermic predators (*color*) than for ectothermic ones (*gray*), whether for a lizard-size system (*a*) or a lion-size one (*b*).




**ENERGY FLOW** and predator-prey relation are illustrated for predator-prey systems of various sizes. Standing crop is the biomass of a population (or the potential energy value contained in the tissue) averaged over a year. For a given adult size, ectothermic prey (*gray*) produce as much meat (*b*) per unit standing crop (*a*) as endotherms (*color*). Endothermic predators, however, require an order of magnitude more meat (*b*) per unit standing crop (*c*). The maximum predator-prey biomass ratio (*c/a*) is therefore about an order of magnitude greater in an endothermic system than it is in an ectothermic one.

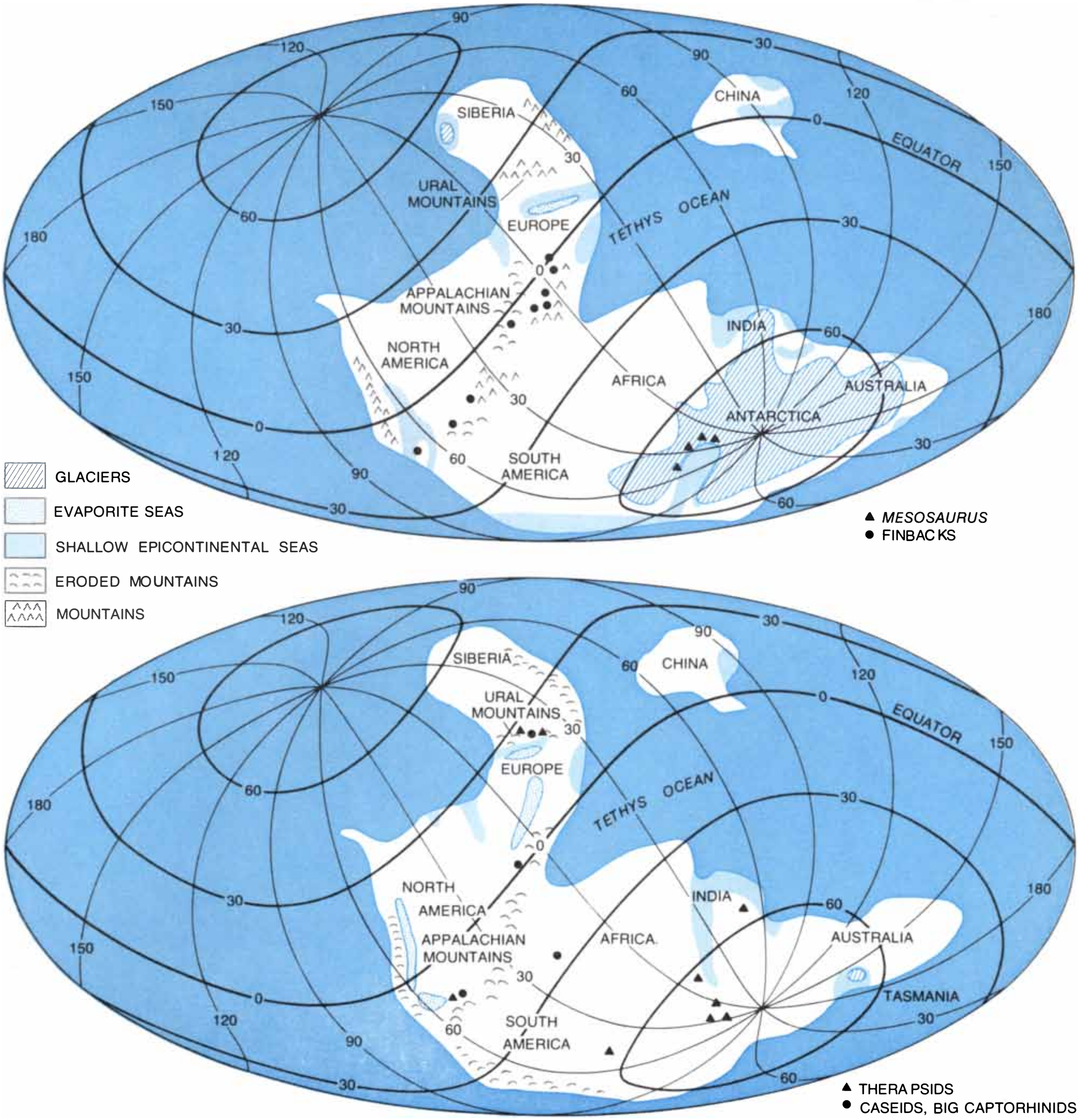
ing is as follows: The energy budget of an endothermic population is an order of magnitude larger than that of an ectothermic population of the same size and adult weight, but the productivity—the yield of prey tissue available to predators—is about the same for both an endothermic and an ectothermic population. In a steady-state population the yearly gain in weight and energy value from growth and reproduction equals the weight and energy value of the carcasses of the animals that die during the year; the loss of biomass and energy through death is balanced by additions. The maximum energy value of all the carcasses a steady-state population of lizards can provide its predators is about the same as that provided by a prey population of birds or mammals of about the same numbers and adult body size. Therefore a given prey population, either ectotherms or endotherms, can support an order of magnitude greater biomass of ectothermic predators than of endothermic predators, because of the endotherms' higher energy needs. The term standing crop refers to the biomass, or the energy value contained in the biomass, of a population. In both ectotherms and endotherms the energy value of carcasses produced per unit of standing crop decreases with increasing adult weight of prey animals: a herd of zebra yields from about a fourth to a third of its weight in prey carcasses a year, but a "herd" of mice can produce up to six times its weight because of its rapid turnover, reflected in a short life span and high metabolism per unit weight.

Now, the energy budget per unit of predator standing crop also decreases with increasing weight: lions require more than 10 times their own weight in meat per year, whereas shrews need 100 times their weight. These two bioenergetic scaling factors cancel each other, so that if the adult size of the predator is roughly the same as that of the prey (and in land-vertebrate ecosystems it usually is), the maximum ratio of predator standing crop to prey standing crop in a steady-state community is a constant independent of the adult body size in the predator-prey system [*see top illustration at left*]. For example, spiders are ectotherms, and the ratio of a spider population's standing crop to its prey standing crop reaches a maximum of about 40 percent. Mountain boomer lizards, about 100 grams in adult weight, feeding on other lizards would reach a similar maximum ratio. So would the giant Komodo dragon lizards (up to 150 kilograms in body weight) preying on deer, pigs and monkeys. Endothermic mammals and birds, on the other hand, reach a maximum predator-prey biomass ratio of only from 1 to 3 percent—whether they are weasel and mouse or lion and zebra [*see bottom illustration on opposite page*].

Some fossil deposits yield hundreds or thousands of individuals representing a single community; their live body weight can be calculated from the reconstruction of complete skeletons, and the total predator-prey biomass ratios are then easily worked out. Predator-prey ratios are powerful tools for paleophysiology because they are the direct result of predator metabolism.

## The Age of Ectothermy

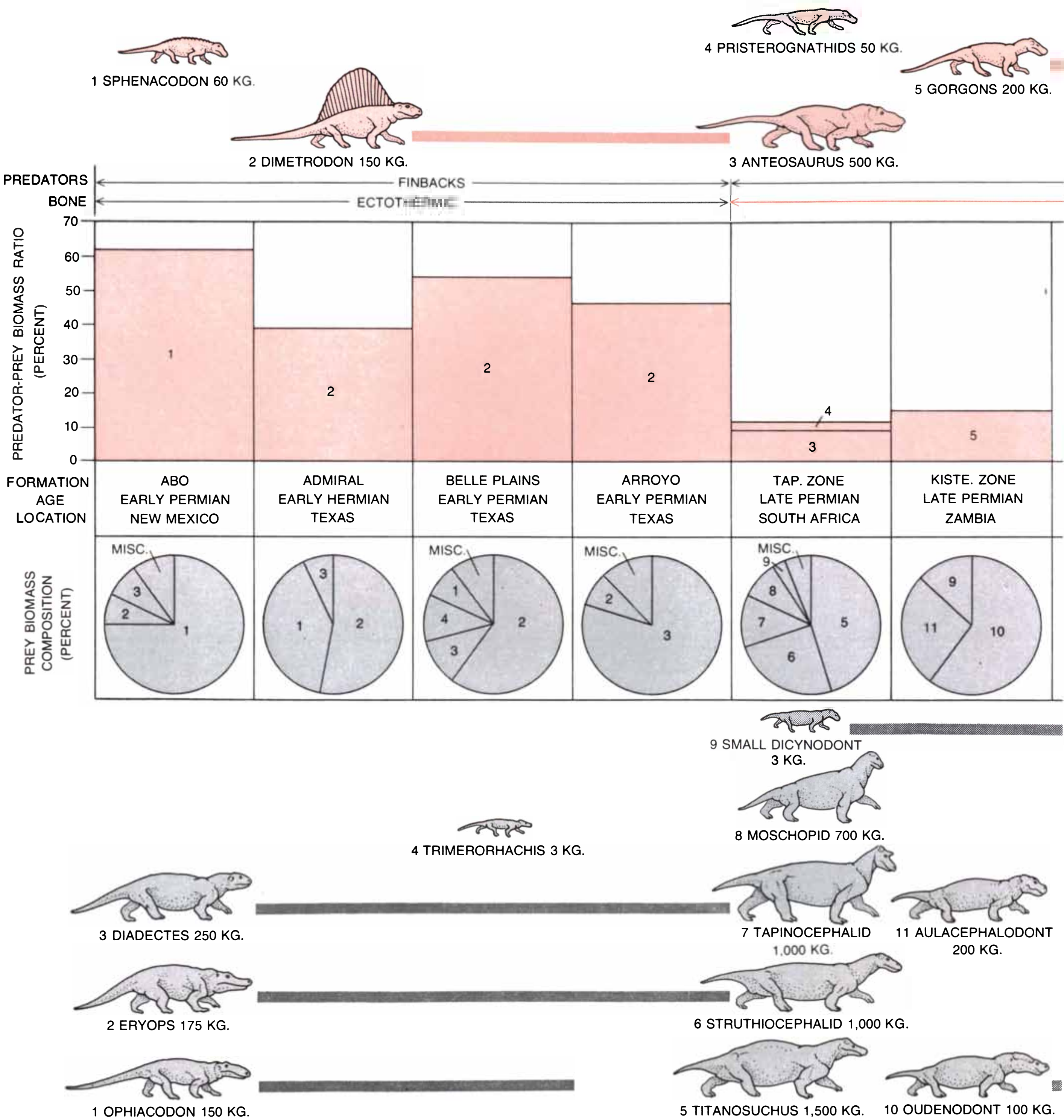
The paleobioenergetic methodology I have outlined can be tested by analyzing



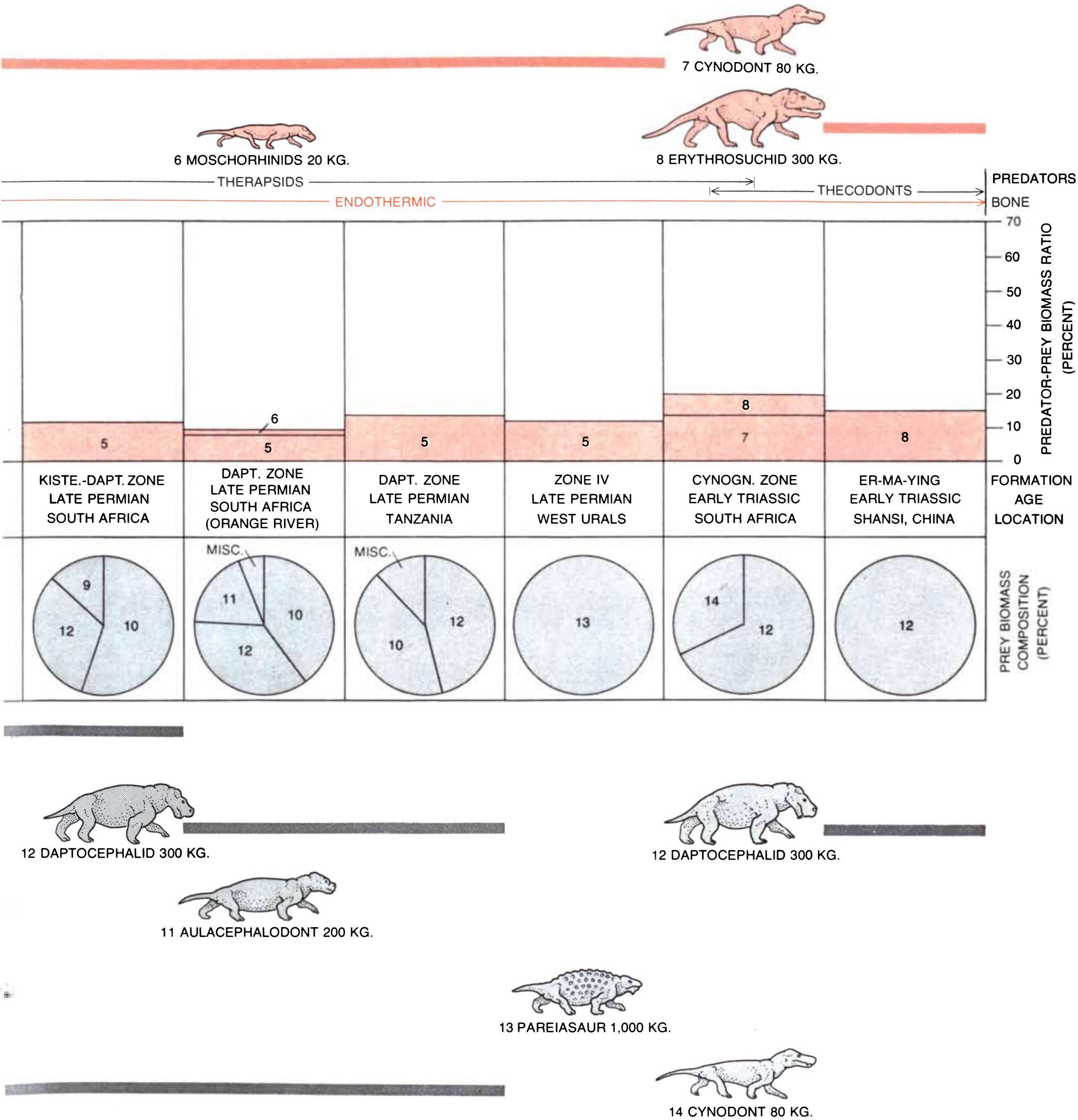

**PERMIAN WORLD is reconstructed here (on an oblique Mollweide projection, which minimizes distortion of area) on the basis of paleomagnetic and other geophysical data. All major land masses except China were welded into a supercontinent, Pangaea. In the early Permian (*top*) the Gondwana glaciation was at its maximum, covering much of the southern part of the continent. Big finback pelycosaurs and contemporary large reptiles and amphibians were confined to the Tropics; they had ectothermic bone and high predator-prey ratios. The only reptile in cold southern Gondwanaland was the little *Mesosaurus*, which apparently hibernated in the mud during the winters. The late Permian world (*bottom*) was less glaciated, but the south was still cold and the latitudinal temperature gradient was still steep. Big reptiles with ectothermic bone, caseids and captorhinids, were restricted to the hot Tropics, as large reptiles had been in the early Permian. By now, however, many early therapsids, all with endothermic bone and low predator-prey ratios, had invaded southern Gondwanaland. They must have acquired high heat production and some insulation.**

the first land-vertebrate predator-prey system, the early Permian communities of primitive reptiles and amphibians. The first predators capable of killing relatively large prey were the finback pelycosaurs of the family Sphenacodontidae, typified by *Dimetrodon*, whose tall-spined fin makes it popular with cartoonists. Although this family included the direct ancestors of mammal-like reptiles and hence of mammals, the sphenacodonts themselves had a very primitive level of organization, with a limb anatomy less advanced than that of living lizards. Finback bone histology was emphatically ectothermic, with a low density of blood vessels, few Haversian canals and the distinct growth rings that are common in specimens from seasonally arid climates.

One might suspect that finbacks and their prey would be confined to warm, equable climates, and early Permian paleogeography offers an excellent op-




**PREDATOR-PREY RATIO AND PREY COMPOSITION** are shown on these two pages and the next two pages for a number of fossil communities, each representing a particular time zone and depositional environment. The predator (*top*) and prey (*bottom*) animals involved at each site are illustrated. For each deposit the histogram (*color*) gives the predator biomass as a percent of the portunity to test this prediction. During the early part of the period ice caps covered the southern tips of the continental land masses, all of which were part of the single southern supercontinent Gondwanaland, and glacial sediment is reported at the extreme northerly tip of the Permian land mass in Siberia by Russian geologists [*see illustration on page 63*]. The Permian Equator crossed what are now the American Southwest, the Maritime Provinces of Canada and western Europe. Here are found sediments produced in very hot climates: thick-bedded evaporite salts and fully oxidized, red-stained mudstones. The latitudinal temperature gradient in the Permian must have been at least as steep as it is at present. Three Permian floral zones reflect the strong poleward temperature gradient. The Angaran flora of Siberia displays wood with growth rings from a wet environment, implying a moist climate with cold winters. The

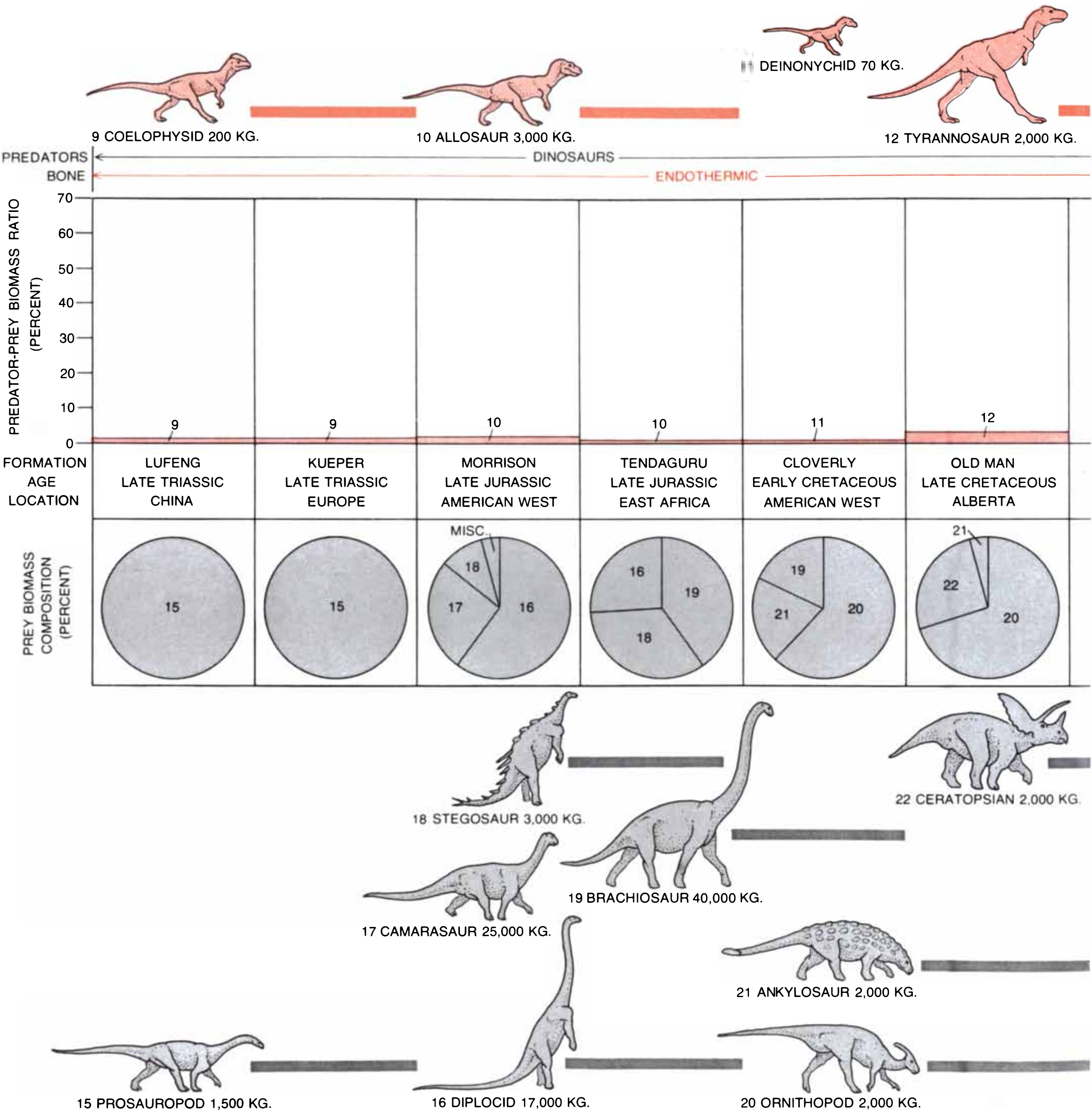



**total prey biomass, in other words, the predator-prey ratio. The pie charts give the composition of the available prey. Note the sudden drop in the predator-prey ratios during the transition from the finback pelycosaurs to the early therapsids, which coincided with the first appearance of endothermic bone and also with the invasion of cold southern Gondwanaland by early therapsids of all sizes.**

Euramerian flora of the equatorial region had two plant associations: wet swamp communities with no growth rings in the wood, implying a continuous warm-moist growing season, and semiarid, red-bed-evaporite communities with some growth rings, reflecting a tropical dry season. In glaciated Gondwanaland the peculiar *Glossopteris* flora dominated, with wood from wet environments showing sharp growth rings.

The ectothermy of the finbacks is confirmed by their geographic zonation. Finback communities are known only from near the Permian Equator; no large early Permian land vertebrates of any kind are found in glaciated Gondwanaland. (One peculiar little fish-eating reptile, *Mesosaurus*, is known from southern Gondwanaland, and its bone has sharp growth rings. The animal must have fed and reproduced during the Gondwanaland summer and then burrowed into the mud of lagoon bottoms to hibernate, much as large snapping turtles do today in New England.)

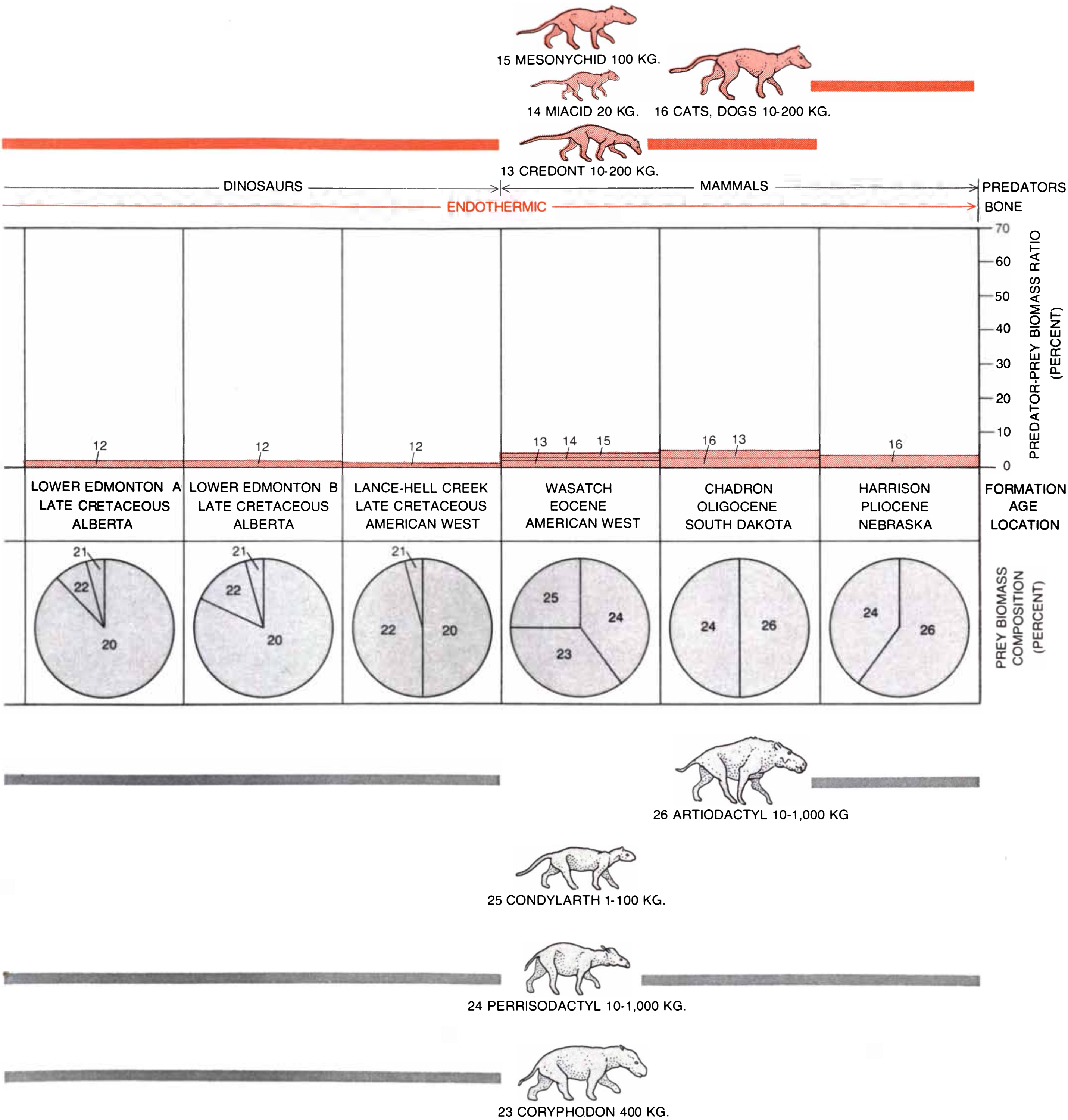
Excellent samples of finback commu-



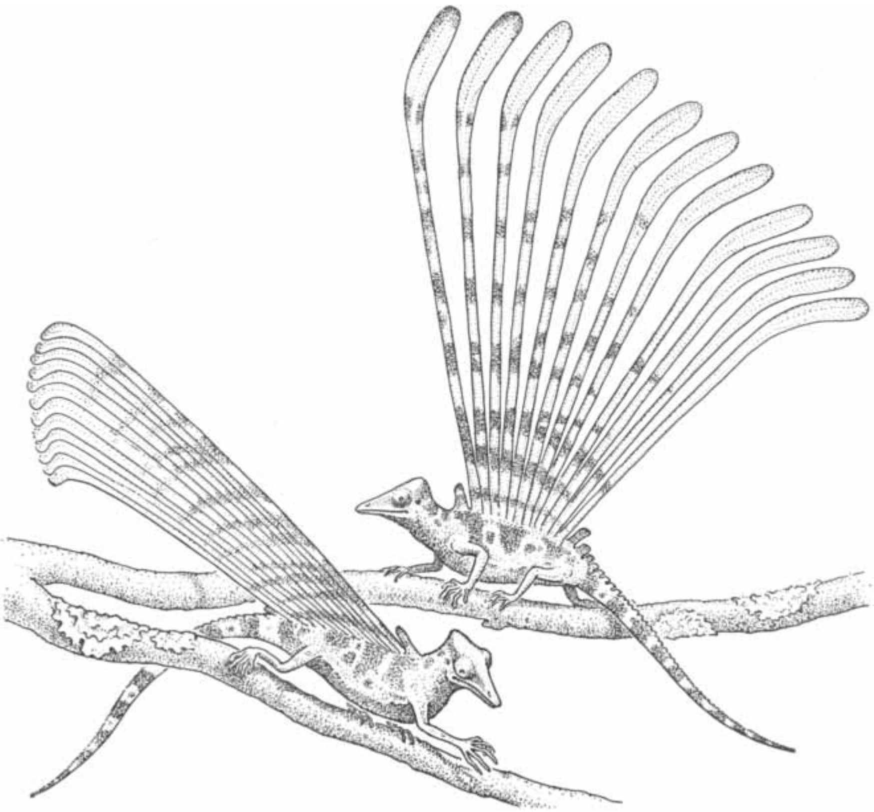

**EVIDENCE FROM FOSSIL COMMUNITIES is continued from the preceding two pages. The animals are of course not all drawn to the same scale; their adult weights are given. The drawings are presented with the same limb-stride positions in each to emphasize**

nities are available for predator-prey studies, thanks largely to the lifework of the late Alfred Sherwood Romer of Harvard University. In order to derive a predator-prey ratio from a fossil community one simply calculates the number of individuals, and thus the total live weight, represented by all the predator and prey specimens that are found together in a sediment representing one particular environment. In working with scattered and disarticulated skeletons it is best to count only bones that have about the same robustness, and hence the same preservability, in both predator and prey. The humerus and the femur are good choices for finback communities: they are about the same size with respect to the body in the prey and the predator and should give a ratio that faithfully represents the ratio of the animals in life.

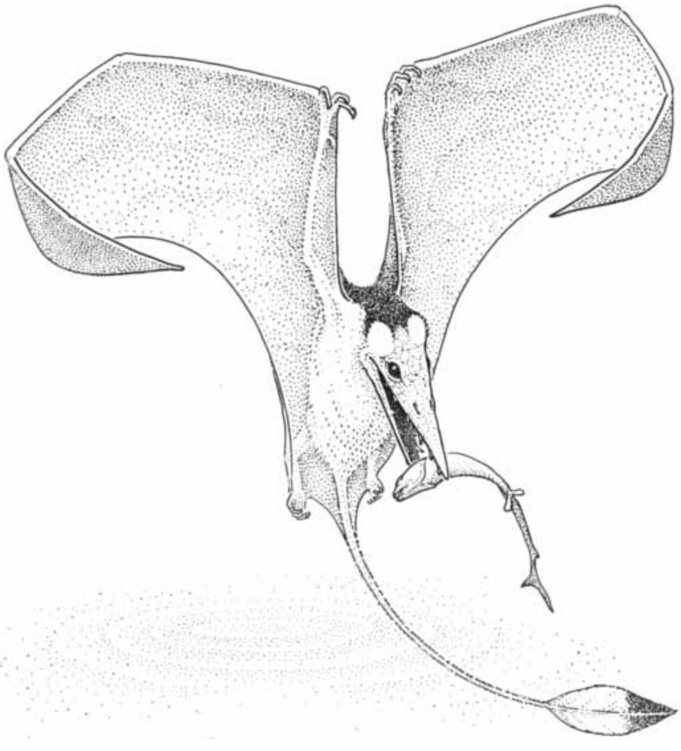
In the earlier early Permian zones the most important finback prey were semiaquatic fish-eating amphibians and reptiles, particularly the big-headed amphibian *Eryops* and the long-snouted




**relative limb length. Long-limbed, fast-sprinting vertebrates of large size appeared only with the dinosaurs, in the middle Triassic. Note the remarkably low predator-prey ratios of the dinosaurs, as low as or lower than those of the Cenozoic (and modern) mammals.**



**LONGISQUAMA, a small animal whose fossil was discovered in middle Triassic lake beds in Turkestan by the Russian paleontologist A. Sharov, was a thecodont. Its body was covered by long overlapping scales that were keeled, suggesting that they constituted a structural stage in the evolution of feathers. The long devices along the back were *V*-shaped in cross section; they may have served as parachutes and also as threat devices, as shown here.**



**SORDUS PILOSUS, also found by Sharov, was a pterosaur: a flying reptile of the Jurassic period that was a descendant of thecodonts or of very early dinosaurs. Superbly preserved fossils show that the animal was insulated with a dense growth of hair or hairlike feathers; hence the name, which means "hairy devil." Insulation strongly suggests endothermy.**

pelycosaur *Ophiacodon*. As the climate became more arid in Europe and America these water-linked forms decreased in numbers, and the fully terrestrial herbivore *Diadectes* became the chief prey genus. In all zones from all environments the calculated biomass ratio of predator to prey in finback communities is very high: from 35 to 60 percent, the same range seen in living ectothermic spiders and lizards.

All three of the paleobioenergetic indicators agree: the finback pelycosaurs and their contemporaries were ectotherms with low heat production and a lizardlike physiology that confined their distribution to the Tropics.

## Therapsid Communities

The mammal-like reptiles (order Therapsida), descendants of the finbacks, made their debut at the transition from the early to the late Permian and immediately became the dominant large land vertebrates all over the world. The three metabolism-measuring techniques show that they were endotherms.

The earliest therapsids retained many finback characteristics but had acquired limb adaptations that made possible a trotting gait and much higher running speeds. From early late Permian to the middle Triassic one line of therapsids became increasingly like primitive mammals in all details of the skull, the teeth and the limbs, so that some of the very advanced mammal-like therapsids (cynodonts) are difficult to separate from the first true mammals. The change in physiology, however, was not so gradual. Detailed studies of bone histology conducted by Armand Riqles of the University of Paris indicate that the bioenergetic transition was sudden and early: all the finbacks had fully ectothermic bone; all the early therapsids—and there is an extraordinary variety of them—had fully endothermic bone, with no growth rings and with closely packed blood vessels and Haversian canals.

The late Permian world still had a severe latitudinal temperature gradient; some glaciation continued in Tasmania, and the southern end of Gondwanaland retained its cold-adapted *Glossopteris* flora. If the earliest therapsids were equipped with endothermy, they would presumably have been able to invade southern Africa, South America and the other parts of the southern cold-temperature realm. They did exactly that. A rich diversity of early therapsid families has been found in the southern Cape District of South Africa, in Rhodesia, in Brazil and in India—regions reaching to 65 degrees south Permian latitude [*see illustration on page 63*]. Early therapsids as large as rhinoceroses were common there, and many species grew to an adult weight greater than 10 kilograms, too large for true hibernation. These early therapsids must have had physiological adaptations that enabled them to feed in and move through the snows of the cold Gondwanaland winters. There were also some ectothermic holdovers from the early Permian that survived into the late Permian, notably the immense herbivorous caseid pelycosaurs and the big-headed, seed-eating captorhinids. As one might predict, large species of these two ectothermic families were confined to areas near the late Permian Equator; big caseids and captorhinids are not found with the therapsids in cold Gondwanaland. In the late Permian, then, there was a "modern" faunal zonation of large vertebrates, with endothermic therapsids and some big ectotherms in the Tropics giving way to an all-endothermic therapsid fauna in the cold south.

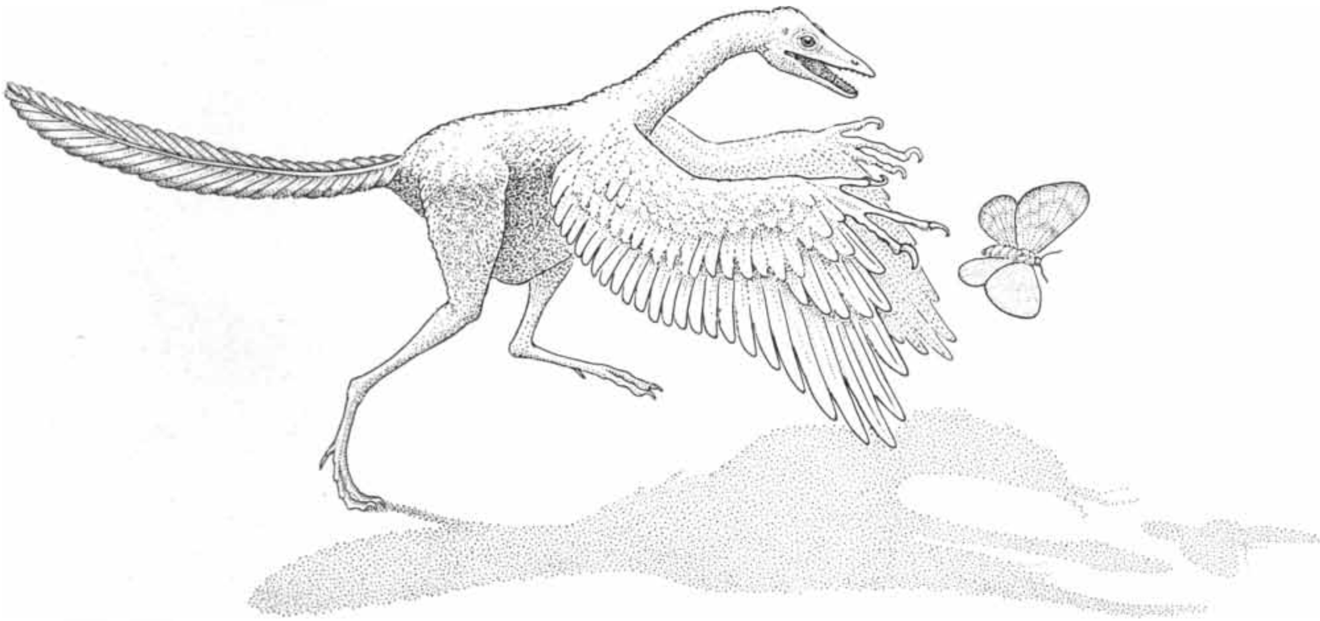
In the earliest therapsid communities of southern Africa, superbly represented in collections built up by Lieuwe Boonstra of the South African Museum and by James Kitching of the University of the Witwatersrand, the predator-prey ratios are between 9 and 16 percent. That is much lower than in early Permian finback communities. Equally low ratios are found for tropical therapsids from the U.S.S.R. even though the prey species there were totally different from those of Africa. The sudden decrease in predator-prey ratios from finbacks to early therapsids coincides exactly with the sudden change in bone histology from ectothermic to endothermic reported by Riqles and also with the sudden invasion of the southern cold-temperate zone by a rich therapsid fauna. The conclusion is unavoidable that even early therapsids were endotherms with high heat production.

It seems certain, moreover, that in the cold Gondwanaland winters the therapsids would have required surface insulation. Hair is usually thought of as a late development that first appeared in the advanced therapsids, but it must have been present in the southern African endotherms of the early late Permian. How did hair originate? Possibly the ancestors of therapsids had touch-sensitive hairs scattered over the body as adaptations for night foraging; natural selection could then have favored increased density of hair as the animals' heat production increased and they moved into colder climates.

The therapsid predator-prey ratios, although much lower than those of ectotherms, are still about three times higher than those of advanced mammals today. Such ratios indicate that the therapsids achieved endothermy with a moderately high heat production, far higher than in typical reptiles but still lower than in most modern mammals. Predator-prey ratios of early Cenozoic communities seem to be lower than those of therapsids, and so one might conclude that a further increase in metabolism occurred somewhere between the advanced therapsids of the Triassic and the mammals of the post-Cretaceous era. Therapsids may have operated at a lower body temperature than most living mammals do, and thus they may have saved energy with a lower thermostat setting. This suggestion is reinforced by the low body temperature of the most primitive living mammals: monotremes (such as the spiny anteater) and the insectivorous tenrecs of Madagascar; they maintain a temperature of about 30 degrees Celsius instead of the 36 to 39 degrees of most modern mammals.

## Thecodont Transition

The vigorous and successful therapsid dynasty ruled until the middle of the Triassic. Then their fortunes waned and a new group, which was later to include the dinosaurs, began to take over the roles of large predators and herbivores. These were the Archosauria, and the first wave of archosaurs were the the-



**ARCHAEOPTERYX, generally considered the first bird, is known from late Jurassic fossils that show its feather covering clearly. In spite of its very birdlike appearance, *Archaeopteryx* was closely related to certain small dinosaurs (*see illustration on next page*) and could not fly. The presence of insulation in the thecodont *Longisquama* and in *Sordus* and *Archaeopteryx*, which were descendants of thecodonts, indicates that insulation and endothermy were acquired very early, probably in early Triassic thecodonts.**

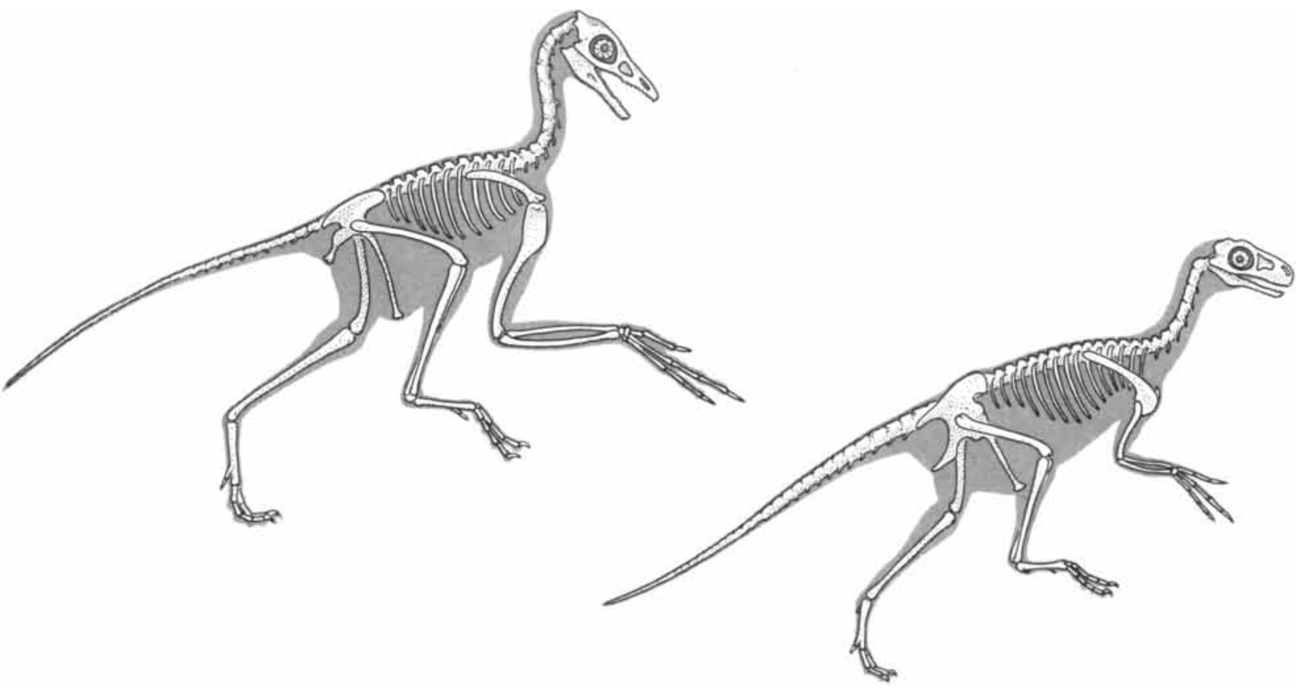
codonts. The earliest thecodonts, small and medium-sized animals found in therapsid communities during the Permian-Triassic transition, had an ectothermic bone histology. In modern ecosystems the role played by large freshwater predators seems to be one in which ectothermy is competitively superior to endothermy; the low metabolic rate of ectotherms may be a key advantage because it allows much longer dives. Two groups of thecodonts became large freshwater fish-eaters: the phytosaurs, which were confined to the Triassic, and the crocodilians, which remain successful today. Both groups have ectothermic bone. (The crocodilian endothermy was either inherited directly from the first thecodonts or derived secondarily from endothermic intermediate ancestors.) In most of the later, fully terrestrial advanced thecodonts, on the other hand, Riqles discovered a typical endothermic bone histology; the later thecodonts were apparently endothermic.

The predator-prey evidence for thecodonts is scanty. The ratios are hard to compute because big carnivorous cynodonts and even early dinosaurs usually shared the predatory role with thecodonts. One sample from China that has only one large predator genus, a big-headed erythrosuchid thecodont, does give a ratio of about 10 percent, which is in the endothermic range. The zonal evidence is clearer. World climate was moderating in the Triassic (the glaciers were gone), but a distinctive flora and some wood growth rings suggest that southern Gondwanaland was not yet warm all year. What is significant in this regard is the distribution of phytosaurs, the big ectothermic fish-eating thecodonts. Their fossils are common in North America and Europe (in the Triassic Tropics) and in India, which was warmed by the equatorial Tethys Ocean, but they have not been found in southern Gondwanaland, in southern Africa or in Argentina, even though a rich endothermic thecodont fauna did exist there.

Did some of the thecodonts have thermal insulation? Direct evidence comes from the discoveries of A. Sharov of the Academy of Sciences of the U.S.S.R. Sharov found a partial skeleton of a small thecodont and named it *Longisquama* for its long scales: strange parachutelike devices along the back that may have served to break the animal's fall when it leaped from trees. More important is the covering of long, overlapping, keeled scales that trapped an insulating layer of air next to its body [*see top illustration on page 68*]. These scales lacked the complex anatomy of real feathers, but they are a perfect ancestral stage for the insulation of birds. Feathers are usually assumed to have appeared only late in the Jurassic with the first bird, *Archaeopteryx.* The likelihood that some thecodonts had insulation is supported, however, by another of Sharov's discoveries: a pterosaur, or flying reptile, whose fossils in Jurassic lake beds still show the epidermal covering. This beast (appropriately named *Sordus pilosus,* the "hairy devil") had a dense growth of hair or hairlike feathers all over its body and limbs. Pterosaurs are descendants of Triassic thecodonts or perhaps of very primitive dinosaurs. The insulation in both *Sordus* and *Longisquama,* and the presence of big erythrosuchid thecodonts at the southern limits of Gondwanaland, strongly suggest that some endothermic thecodonts had acquired insulation by the early Triassic.

## The Dinosaurs

Dinosaurs, descendants of early thecodonts, appeared first in the middle Triassic and by the end of the period had replaced thecodonts and the remaining therapsids as the dominant terrestrial vertebrates. Zonal evidence for endothermy in dinosaurs is somewhat equivocal. The Jurassic was a time of climatic optimum, when the poleward temperature gradient was the gentlest that has prevailed from the Permian until the present day. In the succeeding Cretaceous period latitudinal zoning of ocean-

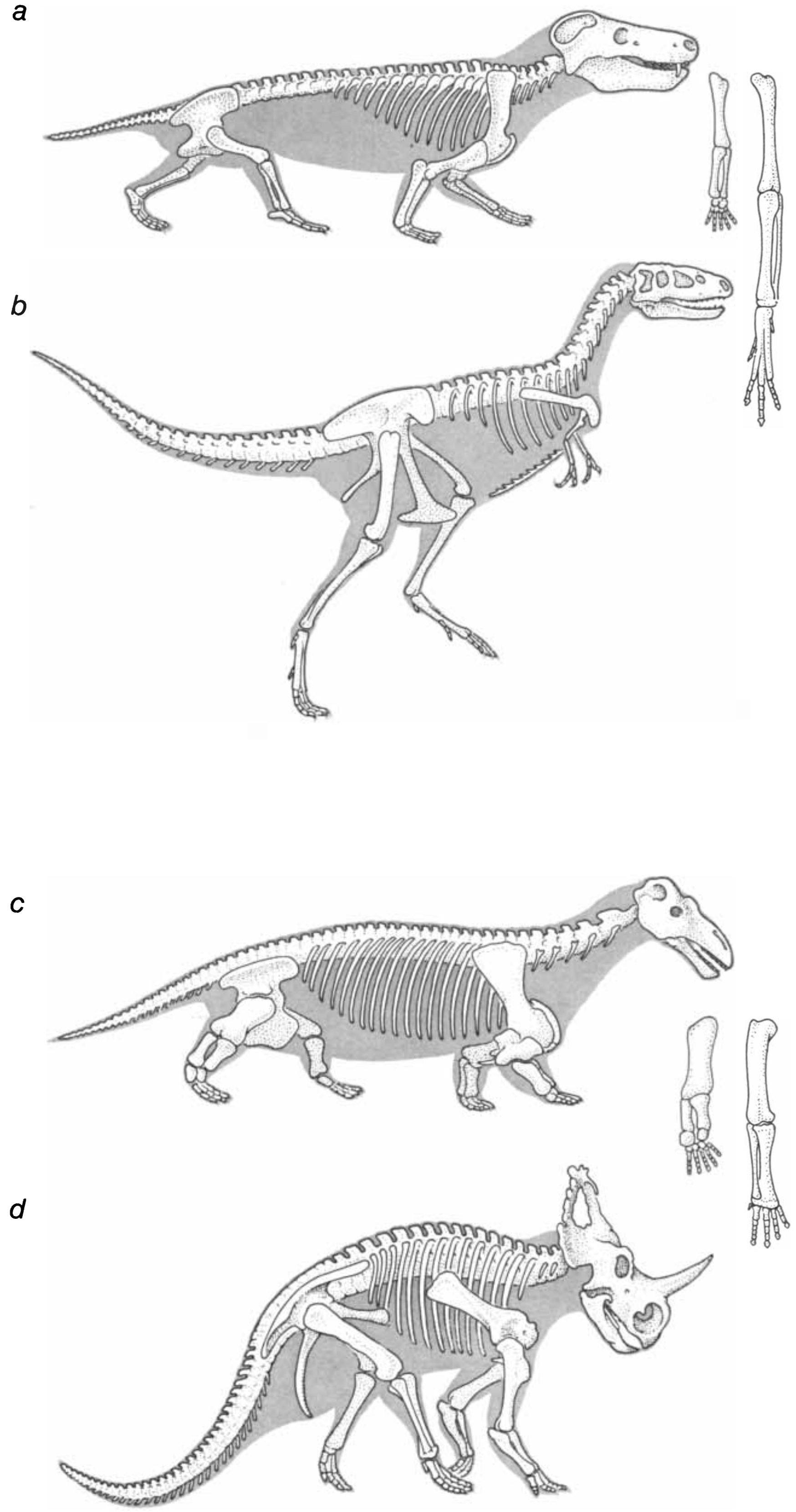


**DINOSAURIAN ANCESTRY of *Archaeopteryx* (*left*), and thus of birds, is indicated by its close anatomical relation to such small dinosaurs as *Microvenator* (*right*) and *Deinonychus*; John H. Ostrom of Yale University demonstrated that they were virtually identical in all details of joint anatomy. The long forelimbs of *Archaeopteryx* were probably used for capturing prey, not for flight.**

ic plankton and land plants seems, however, to have been a bit sharper. Rhinoceros-sized Cretaceous dinosaurs and big marine lizards are found in the rocks of the Canadian far north, within the Cretaceous Arctic Circle. Dale A. Russell of the National Museums of Canada points out that at these latitudes the sun would have been below the horizon for months at a time. The environment of the dinosaurs would have been far severer than the environment of the marine reptiles because of the lack of a wind-chill factor in the water and because of the ocean's temperature-buffering effect. Moreover, locomotion costs far less energy per kilometer in water than on land, so that the marine reptiles could have migrated away from the arctic winter. These considerations suggest, but do not prove, that arctic dinosaurs must have been able to cope with cold stress.

Dinosaur bone histology is less equivocal. All dinosaur species that have been investigated show fully endothermic bone, some with a blood-vessel density higher than that in living mammals. Since bone histology separates endotherms from ectotherms in the Permian and the Triassic, this evidence alone should be a strong argument for the endothermy of dinosaurs. Yet the predator-prey ratios are even more compelling. Dinosaur carnivore fossils are exceedingly rare. The predator-prey ratios for dinosaur communities in the Triassic, Jurassic and Cretaceous are usually from 1 to 3 percent, far lower even than those of therapsids and fully as low as those in large samples of fossils from advanced mammal communities in the Cenozoic. I am persuaded that all the available quantitative evidence is in favor of high heat production and a large annual energy budget in dinosaurs.

Were dinosaurs insulated? Explicit evidence comes from a surprising source: *Archaeopteryx*. As an undergraduate a decade ago I was a member of a paleontological field party led by John H. Ostrom of Yale University. Near Bridger, Mont., Ostrom found a remarkably preserved little dinosaurian carnivore, *Deinonychus*, that shed a great deal of light on carnivorous dinosaurs in general. A few years later, while looking for pterosaur fossils in European museums, Ostrom came on a specimen of *Archaeopteryx* that had been mislabeled for years as a flying reptile, and he noticed extraordinary points of resemblance between *Archaeopteryx* and carnivorous dinosaurs. After a detailed anatomical analysis Ostrom has now established beyond any reasonable doubt that the




**LIMB LENGTHS of dinosaurs are compared with those of two ecologically equivalent therapsids. The limbs were relatively longer in the dinosaurs and the appended muscles were larger, indicating that the dinosaurs had a larger capacity for high levels of exercise metabolism. The two top drawings represent the animals as if they were the same weight; the adult carnivorous therapsid *Cynognathus* (*a*) actually weighed 100 kilograms and the juvenile dinosaur *Albertosaurus* (*b*) 600 kilograms. Two herbivores, therapsid *Struthiocephalus* (*c*) and horned dinosaur *Centrosaurus* (*d*), weighed about 1,500 kilograms.**

immediate ancestor of *Archaeopteryx* must have been a small dinosaur, perhaps one related to *Deinonychus*. Previously it had been thought that the ancestor of *Archaeopteryx*, and thus of birds, was a thecodont rather far removed from dinosaurs themselves.

*Archaeopteryx* was quite thoroughly feathered, and yet it probably could not fly: the shoulder joints were identical with those of carnivorous dinosaurs and were adapted for grasping prey, not for the peculiar arc of movement needed for wing-flapping. The feathers were probably adaptations not for powered flight or gliding but primarily for insulation. *Archaeopteryx* is so nearly identical in all known features with small carnivorous dinosaurs that it is hard to believe feathers were not present in such dinosaurs. Birds inherited their high metabolic rate and most probably their feathered insulation from dinosaurs; powered flight probably did not evolve until the first birds with flight-adapted shoulder joints appeared during the Cretaceous, long after *Archaeopteryx*.

It has been suggested a number of times that dinosaurs could have achieved a fairly constant body temperature in a warm environment by sheer bulk alone; large alligators approach this condition in the swamps of the U.S. Gulf states. This proposed thermal mechanism would not give rise to endothermic bone histology or low predator-prey ratios, however, nor would it explain arctic dinosaurs or the success of many small dinosaur species with an adult weight of between five and 50 kilograms.

## Dinosaur Brains and Limbs

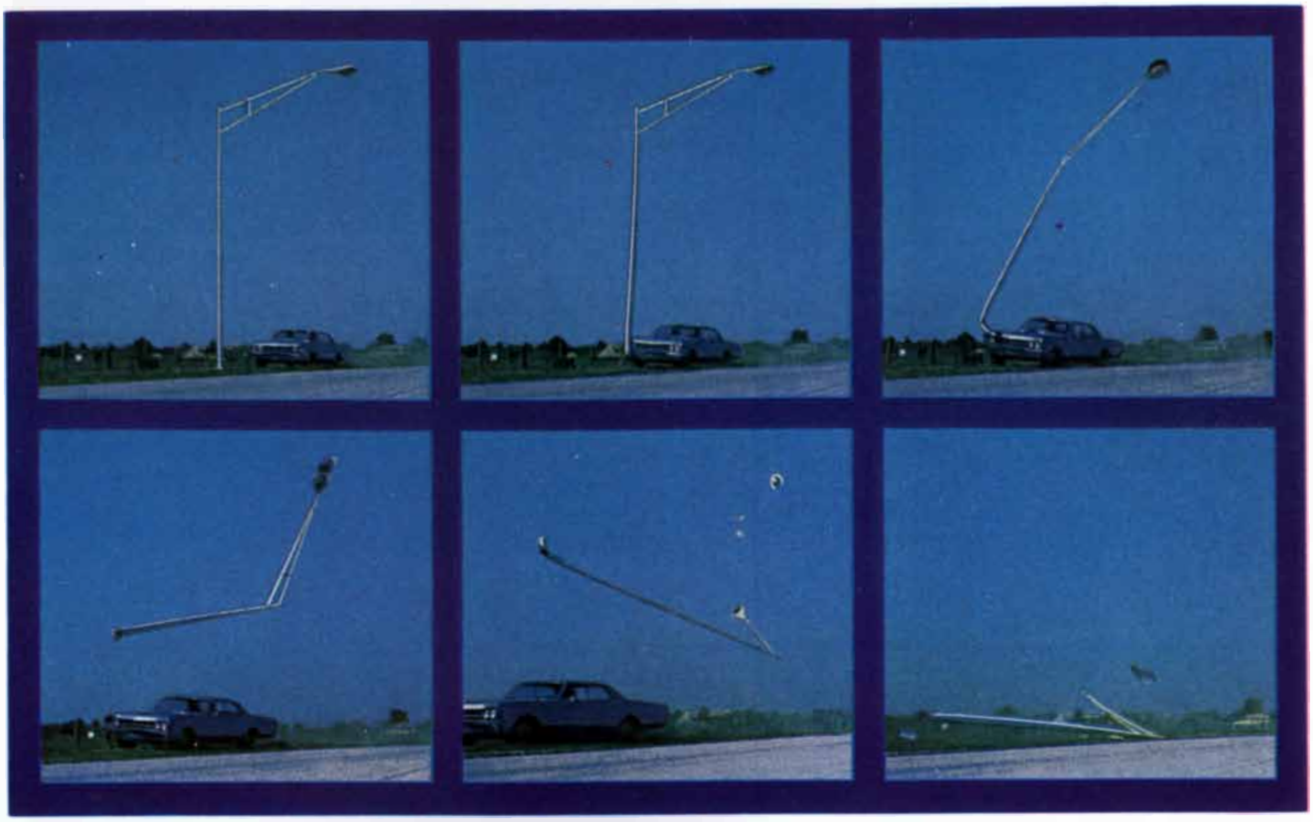
Large brain size and endothermy seem to be linked; most birds and mammals have a ratio of brain size to body size much larger than that of living reptiles and amphibians. The acquisition of endothermy is probably a prerequisite for the enlargement of the brain because the proper functioning of a complex central nervous system calls for the guarantee of a constant body temperature. It is not surprising that endothermy appeared before brain enlargement in the evolutionary line leading to mammals. Therapsids had small brains with reptilian organization; not until the Cenozoic did mammals attain the large brain size characteristic of most modern species. A large brain is certainly not necessary for endothermy, since the physiological feedback mechanisms responsible for thermoregulation are deep within the "old" region of the brain, not in the higher learning centers. Most large dinosaurs did have relatively small brains. Russell has shown, however, that some small and medium-sized carnivorous dinosaurs had brains as large as or larger than modern birds of the same body size.

Up to this point I have concentrated on thermoregulatory heat production. Metabolism during exercise can also be read from fossils. Short bursts of intense exercise are powered by anaerobic metabolism within muscles, and the oxygen debt incurred is paid back afterward by the heart-lung system. Most modern birds and mammals have much higher levels of maximum aerobic metabolism than living reptiles and can repay an oxygen debt much faster. Apparently this difference does not keep small ectothermic animals from moving fast: the top running speeds of small lizards equal or exceed those of small mammals. The difficulty of repaying oxygen debt increases with increasing body size, however, and the living large reptiles (crocodilians, giant lizards and turtles) have noticeably shorter limbs, less limb musculature and lower top speeds than many large mammals, such as the big cats and the hoofed herbivores.

The early Permian ectothermic dynasty was also strikingly short-limbed; evidently the physiological capacity for high sprinting speeds in large animals had not yet evolved. Even the late therapsids, including the most advanced cynodonts, had very short limbs compared with the modern-looking running mammals that appeared early in the Cenozoic. Large dinosaurs, on the other hand, resembled modern running mammals, not therapsids, in locomotor anatomy and limb proportions. Modern, fast-running mammals utilize an anatomical trick that adds an extra limb segment to the forelimb stroke. The scapula, or shoulder blade, which is relatively immobile in most primitive vertebrates, is free to swing backward and forward and thus increase the stride length. Jane A. Peterson of Harvard has shown that

| | BONE HISTOLOGY | PRESENT IN TEMPERATE ZONE | PREDATOR–PREY RATIO | LIMB LENGTH |
|---|---|---|---|---|
| FINBACKS, OTHER EARLY PERMIAN LAND VERTEBRATES | | NO | 50 PERCENT | SHORT |
| LATE PERMIAN CASEIDS AND BIG CAPTORHINIDS | | NO | NOT APPLICABLE | SHORT |
| LATE PERMIAN–EARLY TRIASSIC THERAPSIDS | | YES | 10 PERCENT | SHORT |
| EARLIEST THECODONTS | | ? | ? | SHORT |
| MOST LAND THECODONTS | | YES UP TO 600 KILOGRAMS | 10 PERCENT | SHORT |
| FRESHWATER THECODONTS | | NO UP TO 500 KILOGRAMS | ? | SHORT |
| DINOSAURS | | YES | 1–3 PERCENT | LONG |
| CENOZOIC MAMMALS | | YES | 1–5 PERCENT | LONG |

**PALEOBIOENERGETIC EVIDENCE is summed up here. The appropriate blocks are shaded to show whether the available data constitute evidence for ectothermy (*gray*) or endothermy (*color*) according to criteria discussed in the text of this article. Caseids and captorhinids are herbivores, so that there is no predator-prey ratio. There are early thecodonts in temperate-zone deposits, but they are small and so the evidence is not significant.**



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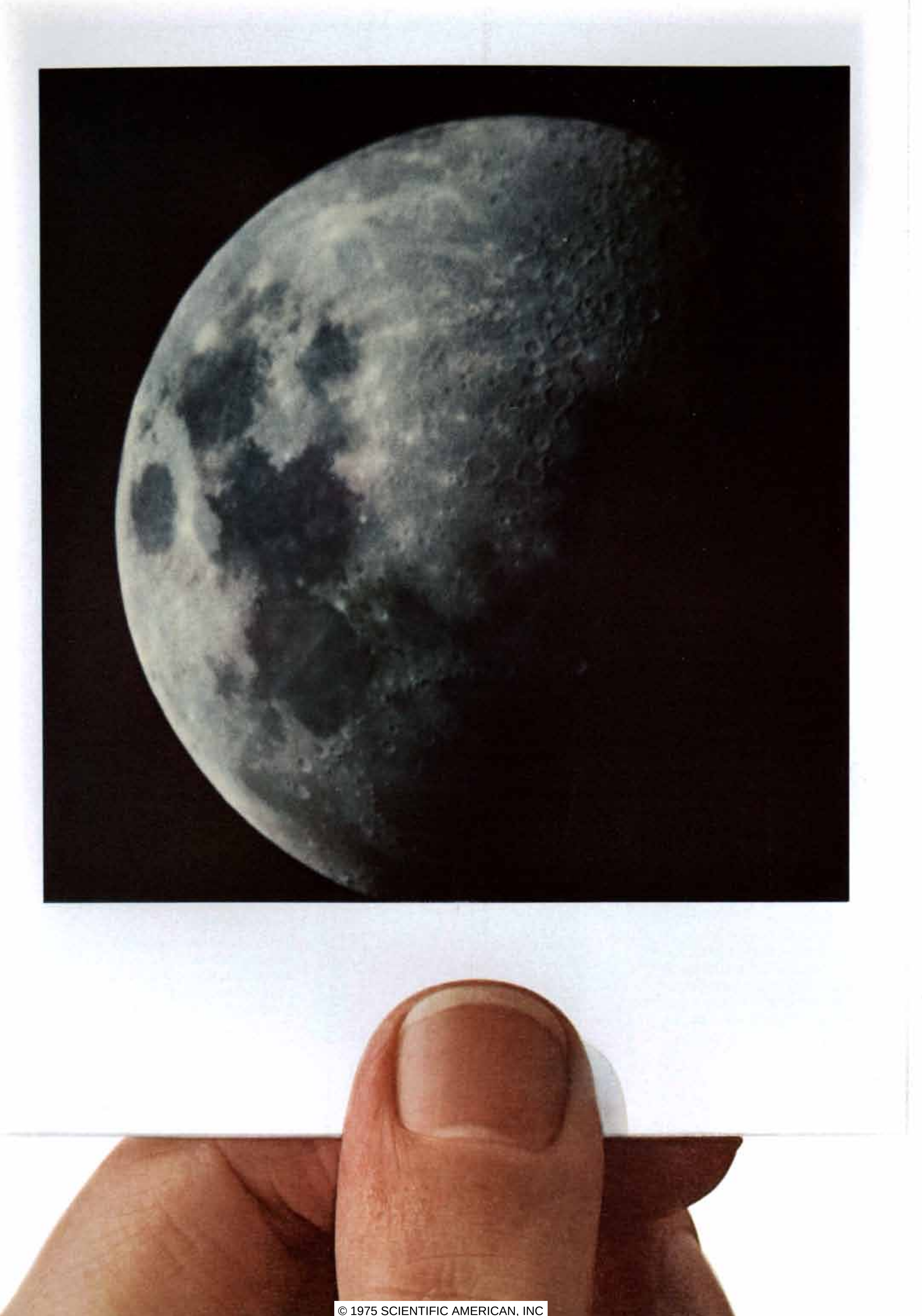

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# Conversation Pieces

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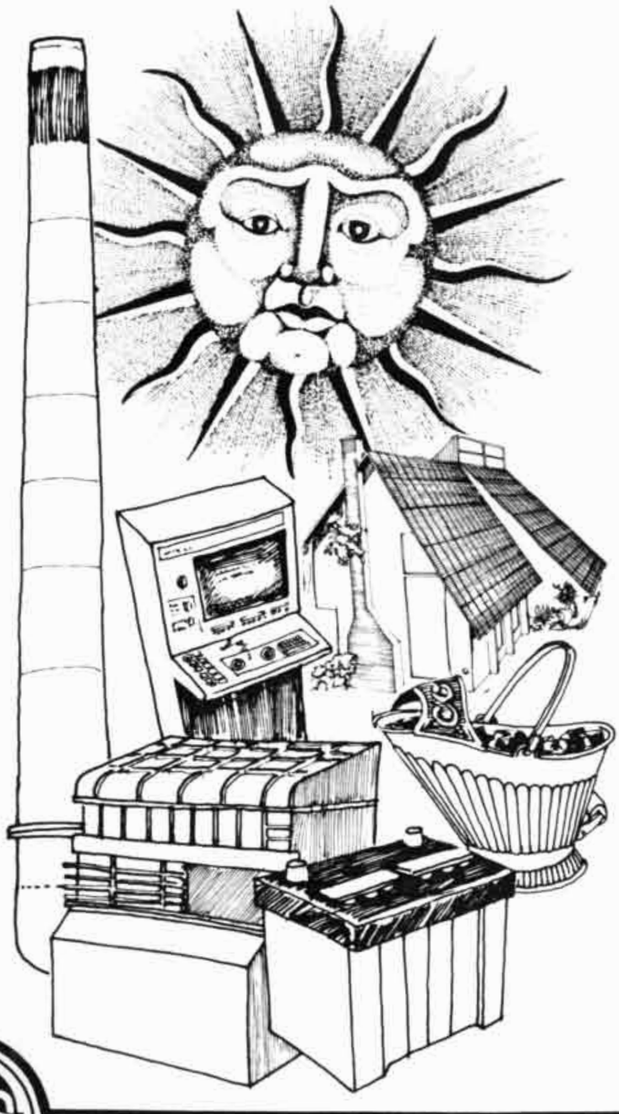

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The total energy problem, however, is the most challenging of all. It requires objective trade-offs between supply, conversion, and distribution capabilities and the varying parameters of demand. Of real value here is the fact that our people are not directly involved in the production of fuels. This frees them to ask the kind of basic questions that are essential to objective analysis.

Our work in space technology, which may seem irrelevant to energy problems, also turns out to be useful. Among other things, it has given us a lot of experience in using very little energy with maximum efficiency.

Our most recent interplanetary probe, for example, has just enough power to light an ordinary desk lamp; yet it warms components in temperatures far below zero... energizes a whole complex of sensing, recording, and computing systems... and transmits streams of pictures and other data over distances as great as half a billion miles.

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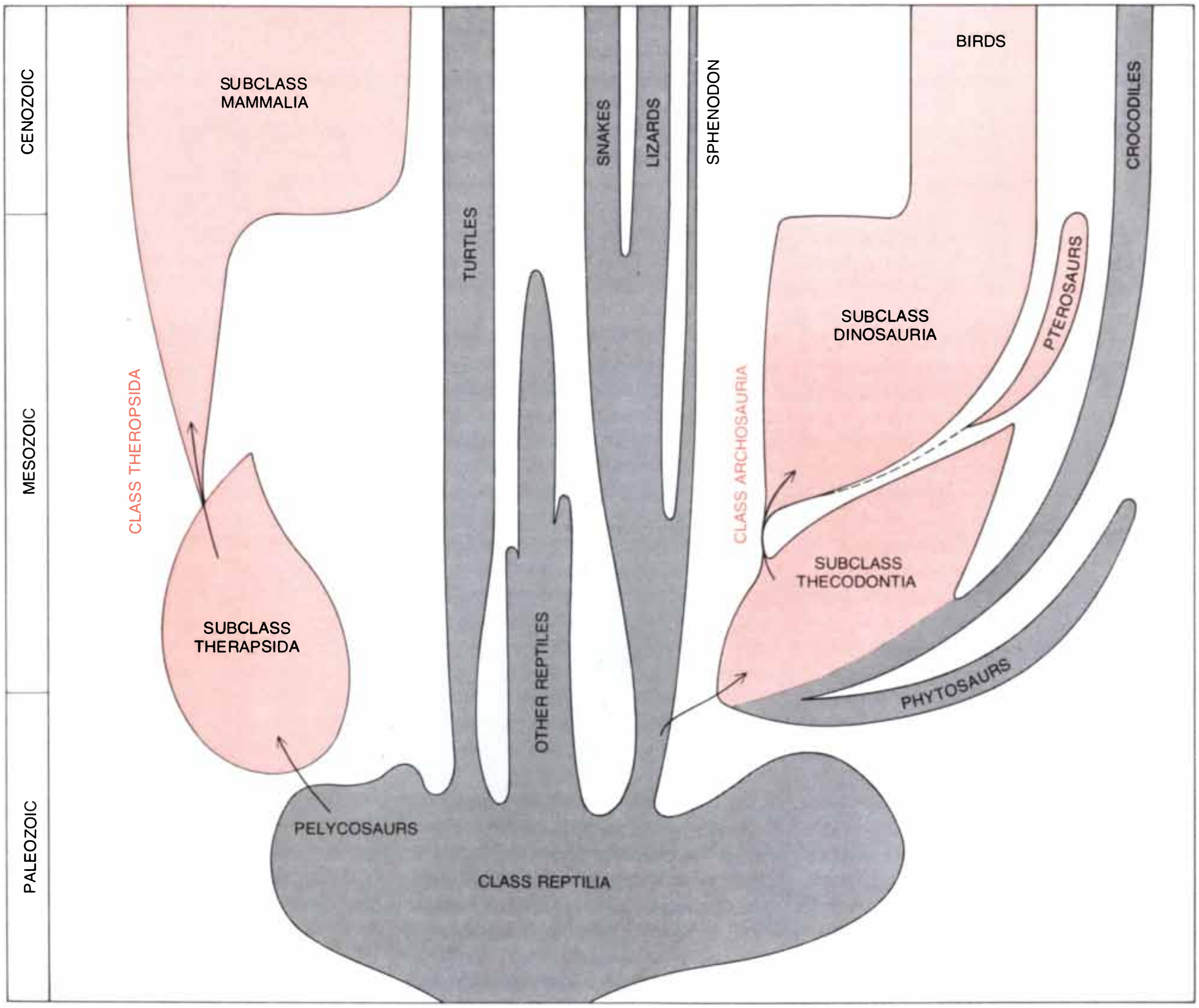
living chameleonid lizards have also evolved scapular swinging, although its details are different from those in mammals. Quadrupedal dinosaurs evolved a chameleon-type scapula, and they must have had long strides and running speeds comparable to those of big savanna mammals today.

When the dinosaurs fell at the end of the Cretaceous, they were not a senile, moribund group that had played out its evolutionary options. Rather they were vigorous, still diversifying into new orders and producing a variety of big-brained carnivores with the highest grade of intelligence yet present on land. What caused their fall? It was not competition, because mammals did not begin to diversify until after all the dinosaur groups (except birds!) had disappeared. Some geochemical and microfossil evidence suggests a moderate drop in ocean temperature at the transition from the Cretaceous to the Cenozoic, and so cold has been suggested as the reason. But the very groups that would have been most sensitive to cold, the large crocodilians, are found as far north as Saskatchewan and as far south as Argentina before and immediately after the end of the Cretaceous. A more likely reason is the draining of shallow seas on the continents and a lull in mountain-building activity in most parts of the world, which would have produced vast stretches of monotonous topography. Such geological events decrease the variety of habitats that are available to land animals, and thus increase competition. They can also cause the collapse of intricate, highly evolved ecosystems; the larger animals seem to be the more affected. At the end of the Permian similar changes had been accompanied by catastrophic extinctions among therapsids and other land groups. Now, at the end of the Cretaceous, it was the dinosaurs that suffered a catastrophe; the mammals and birds, perhaps because they were so much smaller, found places for themselves in the changing landscape and survived.

The success of the dinosaurs, an enigma as long as they were considered




**RECLASSIFICATION of land vertebrates (excluding the Amphibia) is suggested by the author on the basis of bioenergetic and anatomical evidence. The critical break comes with the development of endothermy (*color*), which is competitively superior to ectothermy (*gray*) for large land vertebrates. Therapsids were endothermic, closer in physiology to mammals than to today's reptiles. Birds almost certainly inherited their bioenergetics (as well as their joint anatomy) from dinosaurs. The new classes presented here, the Theropsida and the Archosauria, reflect energetic evolution more faithfully than the traditional groupings (*see illustration on page 61*). The width of the pathways representing the various groups is proportional to the biomass represented by their fossils.**

"cold-blooded," can now be seen as the predictable result of the superiority of their high heat production, high aerobic exercise metabolism and insulation. They were endotherms. Yet the concept of dinosaurs as ectotherms is deeply entrenched in a century of paleontological literature. Being a reptile connotes being an ectotherm, and the dinosaurs have always been classified in the subclass Archosauria of the class Reptilia; the other land-vertebrate classes were the Mammalia and the Aves. Perhaps, then, it is time to reclassify.

## Taxonomic Conclusion

What better dividing line than the invention of endothermy? There has been no more far-reaching adaptive breakthrough, and so the transition from ectothermy to endothermy can serve to separate the land vertebrates into higher taxonomic categories. For some time it has been suggested that the therapsids should be removed from the Reptilia and joined with the Mammalia; in the light of the sudden increase in heat production and the probable presence of hair in early therapsids, I fully agree. The term Theropsida has been applied to mammals and their therapsid ancestors. Let us establish a new class Theropsida, with therapsids and true mammals as two subclasses [*see illustration on preceding page*].

How about the class Aves? All the quantitative data from bone histology and predator-prey ratios, as well as the dinosaurian nature of *Archaeopteryx*, show that all the essentials of avian biology—very high heat production, very high aerobic exercise metabolism and feathery insulation—were present in the dinosaur ancestors of birds. I do not believe birds deserve to be put in a taxonomic class separate from dinosaurs. Peter Galton of the University of Bridgeport and I have suggested a more reasonable classification: putting the birds into the Dinosauria. Since bone histology suggests that most thecodonts were endothermic, the thecodonts could then be joined with the Dinosauria in a great endothermic class Archosauria, comparable to the Theropsida. The classification may seem radical at first, but it is actually a good deal neater bioenergetically than the traditional Reptilia, Aves and Mammalia. And for those of us who are fond of dinosaurs the new classification has a particularly happy implication: The dinosaurs are not extinct. The colorful and successful diversity of the living birds is a continuing expression of basic dinosaur biology.

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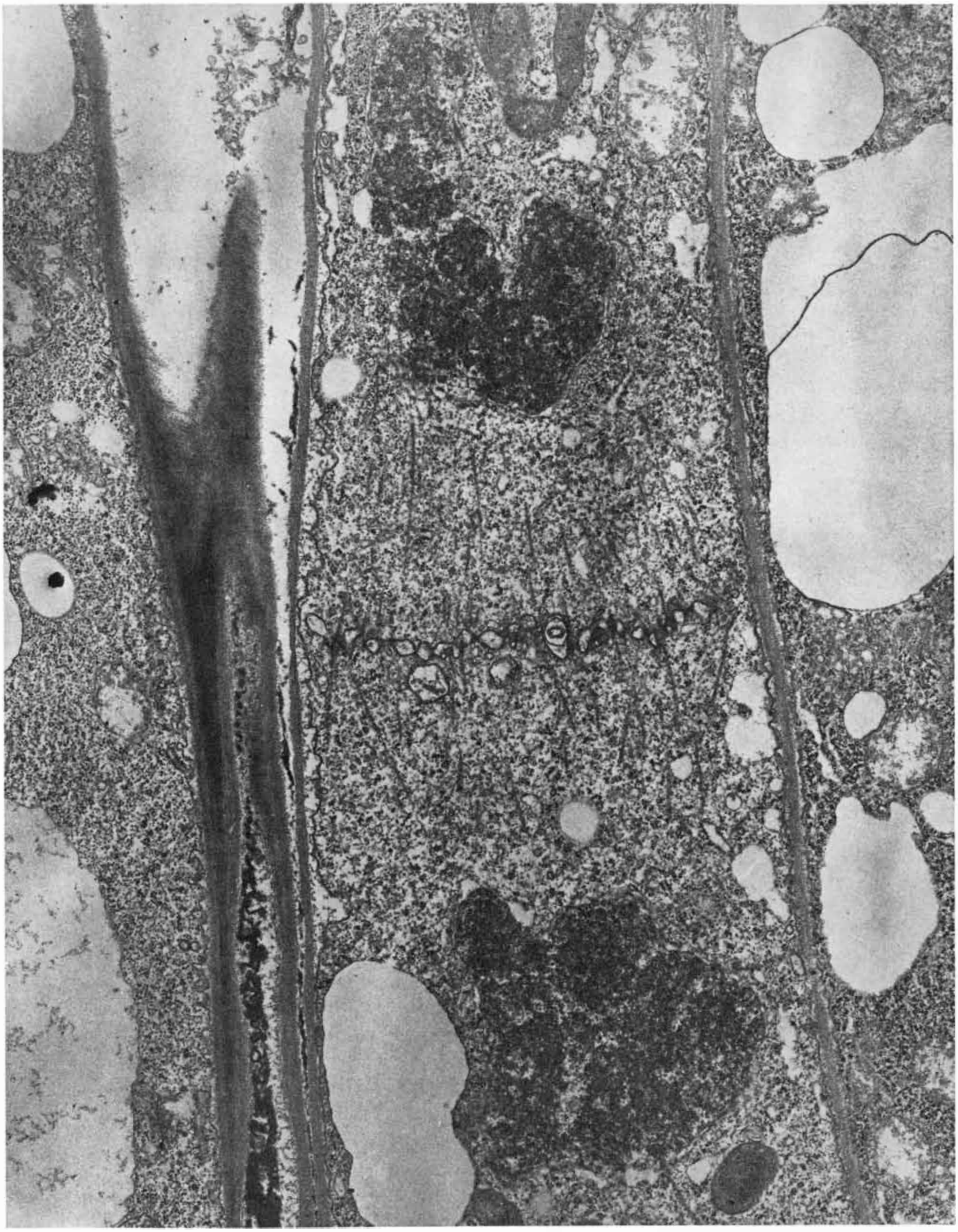


**NEW CELL WALL** bisects a dividing plant cell in an electron micrograph of tissue from the root tip of a maple seedling. The new wall consists of numerous vesicles (lined up horizontally in the middle of the micrograph) that will coalesce to create a barrier continuous with the walls of surrounding cells. The vertical gray lines are established walls, at this stage of development called primary walls; when they have differentiated, they will become secondary walls. Only cells surrounded by primary walls are capable of growth. Just inside the walls is the plasma membrane, which contains the cytoplasm; the amorphous areas of dark gray are cell nuclei, white areas are vacuoles. The micrograph was made by B.A. Palevitz and Eldon H. Newcomb of the University of Wisconsin.

# The Walls of Growing Plant Cells

*They consist of cellulose fibers bound together by molecules made of many sugar units. The structure of those molecules is now known well enough to account for some of the properties of the cell wall*

by Peter Albersheim

Plant cells are encased in a more or less rigid envelope: the cell wall. This wall presents a paradox: it must be stiff enough to give the plant strength and form, yet it must yield freely so that the cell it encloses can grow.

The structural framework of the plant, analogous to both the skin and the bones of an animal, is made up of many cell walls linked together. Adjoining cells are separated by a single wall, just as adjoining rooms in an apartment are separated by a single partition. The shared walls form a dense network of small compartments. In some plants (notably those with woody stems) the strength of the network is prodigious, and the cell walls often endure long after the plant itself has died. In spite of their tough sheathing, however, the cells of growing plant tissues are able to extend to many times their initial length; in response to the demands of growth, cell walls behave as if they were quite pliant.

The remarkable mechanical properties of the cell wall can be explained only if we first understand its structure. In our laboratory at the University of Colorado my colleagues and I have investigated the nature of the constituent molecules that make up the wall, and we have devised a model of how those molecules might be fitted together to produce a wall with the observed characteristics. The model remains tentative, but it provides a basis for reasonable speculation on how the cell wall grows.

The cell wall lies outside the plasma membrane, which defines the boundary of the cell itself. The wall is freely permeable to virtually all molecules, but the membrane is only selectively permeable, and it tends to concentrate certain dissolved molecules and ions inside the cell. As a consequence water diffuses through the membrane by osmosis, increasing the pressure within the cell and pressing the plasma membrane against the cell wall. The membrane is elastic, and if it were not restrained by the wall, it would burst. It is this osmotic pressure that powers the growth of the plant. The rate at which the wall yields to the pressure determines the rate at which the cell enlarges and the rate at which the plant as a whole grows.

Two processes are involved in the growth of plants: cell division and cell elongation. Cell division takes place only in specialized tissues, called meristematic regions, commonly found at the tips of roots and stems and in the buds that form leaves and flowers. Grasses have a meristematic region near the ground between the leaves and the roots; grains have meristem tissue at each node where leaves arise from the stem. When a meristem cell divides, the replication of the genetic material and the separation of the two cell nuclei are followed by the creation of a new transverse wall across the cell. The wall begins as a string of disconnected vesicles in the cytoplasm, but these soon coalesce to form a partition that divides the cell in two [*see illustration on opposite page*].

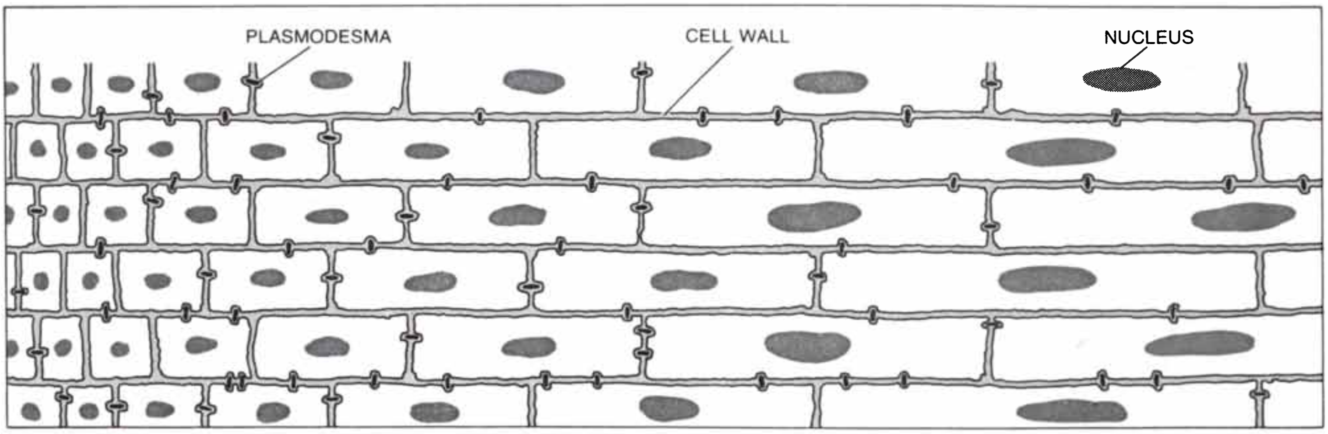
Cell division is necessary for growth, but it produces no direct increase in volume: each of the daughter cells has about half of the volume of the mother cell. The actual increase in the size of the plant results entirely from the enlargement of the daughter cells. The newly formed cells elongate, and before they stop growing they may increase their length as much as a hundredfold. In a longitudinal section of growing plant tissue, such as a root tip, the cells become progressively longer with distance from the meristematic region [*see top illustration on next page*].

It is significant that the growing cells elongate, that is, they grow in only one dimension. The osmotic pressure of the cell, if unconstrained by external forces, would tend to produce spherical expansion. The cell walls, however, confine the enlargement to a single axis and thus determine the shape of the cell as well as its rate of growth.

As long as the cell continues to grow its shape remains nondescript and the walls surrounding it remain relatively thin; in this stage of development they are called primary cell walls. After the cell has matured the walls become thicker, and they may take on a distinctive shape and specialized properties; they are then called secondary walls. The processes of differentiation that transform primary walls into secondary walls are poorly understood. Each type of mature cell in the plant has a characteristic secondary wall, which presumably is adapted to the particular function of the cell. We have confined our investigation to primary walls, which are the only walls capable of growth.

The characteristics of the primary wall during the elongation of the cell have been studied by many investigators. Peter B. Kaufman and his colleagues at the University of Michigan, for example, have grown meristematic regions excised from oat stems in a medium that suppresses cell division but encourages elongation. In collaboration with our laboratory Kaufman has demonstrated that the walls of elongated oat cells have the same thickness and the same strength per unit length as the walls of cells that have not begun to grow. We have also shown that the chemical composition of the walls is not changed by elongation.

Observations such as these compel a number of conclusions. First, the growth of the cell cannot depend on a thinning



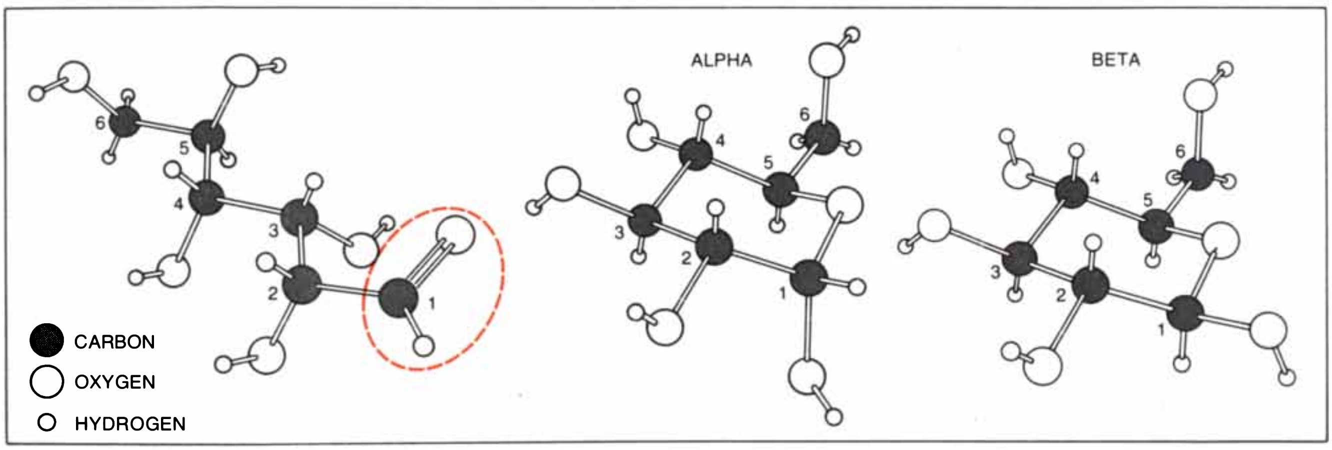

**GROWTH OF PLANT CELLS** is limited by the rate at which the cell walls expand. The walls form a continuous network in which each cell is separated from its neighbor by a single partition. At intervals the walls are pierced by structures called plasmodesmata, through which the cytoplasm of adjacent cells can communicate. The walls control not only the rate of growth but also its direction; they do not expand spherically but elongate in a single dimension. Cells at the left have recently emerged from a meristematic region, the specialized tissue where all cell division takes place; cells farther to the right have started to elongate and are older and longer.

or weakening of the wall. Since the growing wall maintains its thickness and its strength, new material must be added to it. Moreover, the material must be added in such a way that the average chemical composition of the wall is not altered. Finally, these findings imply that both the rate of cell growth and the direction of growth are determined by the structure of the cell wall and the way it is synthesized.

The primary cell wall consists almost entirely of polysaccharides: large molecules made up of many single sugar units, or monosaccharides. Ninety percent of the structural material of the wall is polysaccharide. (The remaining 10 percent is protein.)

Most of the monosaccharides of the cell wall are pentoses and hexoses; their molecules have five or six carbon atoms, along with hydrogen and oxygen atoms in the same ratio as the ratio of those elements in water. It is because such molecules seemed to early investigators to be compounds of carbon and water that they are called carbohydrates. Glucose is the most abundant carbohydrate, and its structure could be considered as being typical of the monosaccharides found in the cell wall. In aqueous solution glucose exists as an open chain of six carbon atoms or as a ring in which an oxygen atom connects the first and the fifth carbon atoms. When it is in the open-chain configuration, glucose has an aldehyde group (–CHO) at the first carbon. The aldehyde is capable of reducing other molecules and ions, that is, it can donate electrons to them. In the ring form the first carbon has a hydrogen atom and a hydroxyl group (–OH) instead of an aldehyde, and it no longer behaves as a reductant. The hydrogen atom and the hydroxyl group can be oriented in two ways, designated alpha and beta [*see illustration below*]. In solution the open-chain form and the alpha and beta ring forms are continually interconverted.

Monosaccharides bind to one another through the distinctive linkage called the glycosidic bond. The bond is a covalent one, in which atoms share pairs of electrons. It is formed when the first carbon atom of a sugar in the ring configuration is linked to a different carbon




**SUGAR MOLECULES** can assume three different structures in solution. In the open-chain form (*left*) the first carbon atom bears an aldehyde group (*colored circle*), which is capable of reducing, or donating electrons to, other molecules and ions. In the ring configuration an oxygen atom links the first and fifth carbon atoms. In the ring form there is no aldehyde group, but the hydroxyl group (–OH) and hydrogen atom attached to the first carbon atom can be oriented in either of two ways; one is designated alpha (*center*), the other beta (*right*). In solution molecules are continuously converted from one form to the other. The molecule shown is glucose.

atom of another sugar. A molecule of water is extracted from the hydroxyl groups attached to both atoms, leaving a single oxygen atom connecting the two sugar units.

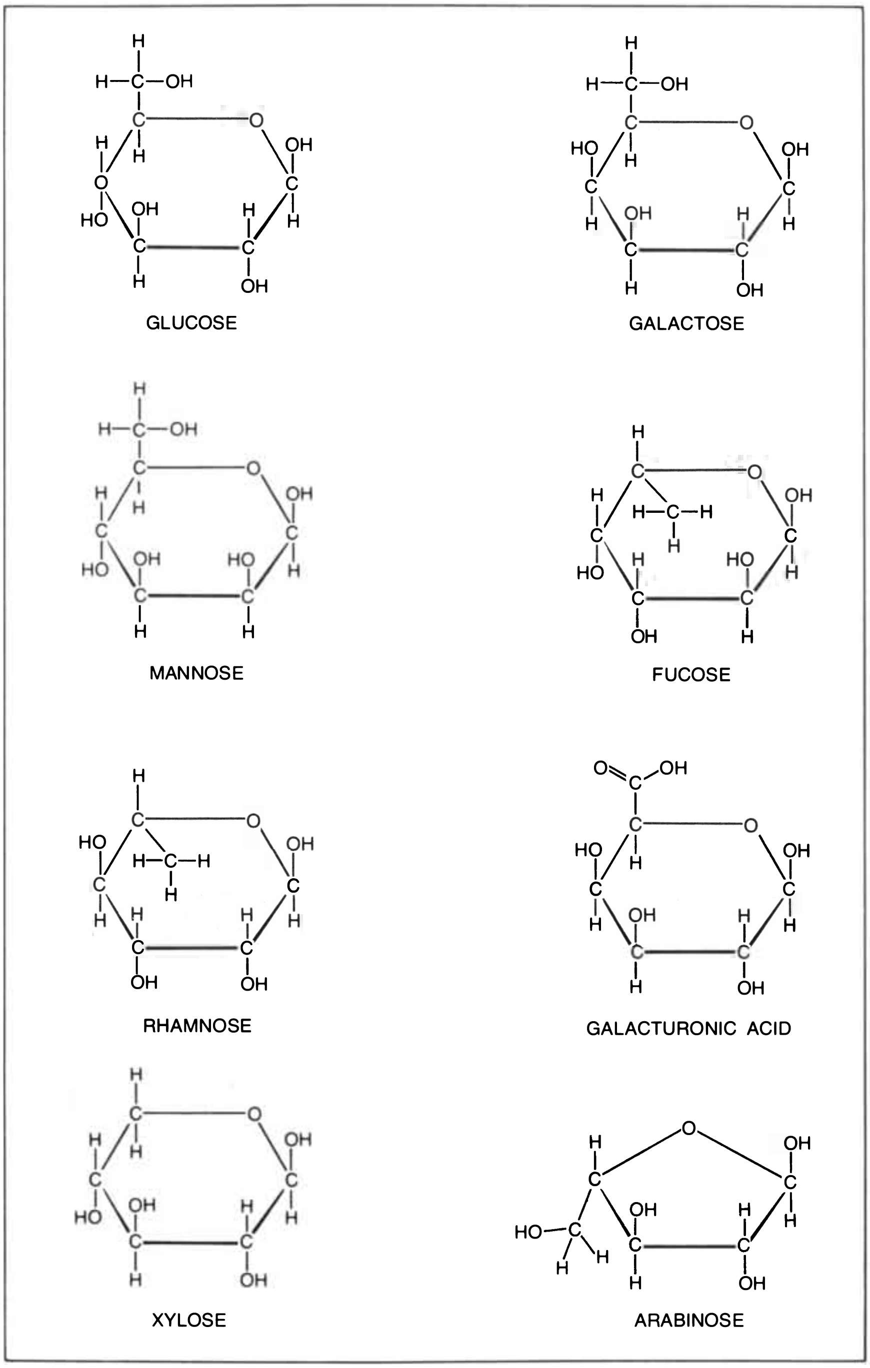
Because the hydroxyl group attached to the first carbon atom of a sugar molecule in the ring formation can have either of two orientations, there are two kinds of glycosidic bond, alpha and beta. Although the difference between them seems small, changing from one kind of glycosidic bond to the other can radically alter the properties of the molecule. When glucose molecules, for example, are linked together by glycosidic bonds between the first and the fourth carbon atoms, alpha bonds and beta bonds produce quite different substances. Two glucose molecules joined by an alpha bond form the disaccharide maltose; many glucose molecules linked the same way make starch, a carbohydrate employed by plants for energy storage. A beta bond in the same position between two glucose molecules produces the disaccharide cellobiose; a long chain of molecules connected by beta bonds is the polysaccharide cellulose. In chemical composition cellulose is identical with starch, but its properties are very different; it is an important structural material of the cell wall.

Polysaccharides are named for the monosaccharides of which they are composed, but the -ose suffix that designates a single sugar is replaced by the suffix -an. Thus the long chains of glucose units that make up both starch and cellulose are called glucans. Starch is an alpha-glucan; cellulose is a beta-glucan. At one end of such a polysaccharide chain there is always a single sugar unit that can unfold into the open chain form, exposing its reducing aldehyde group. That end of the chain is called the reducing end of the polysaccharide.

The glycosidic bonds of polysaccharides can be broken by the catalytic agency of enzymes. Such enzymes are highly specific: typically they can act only on a single kind of glycosidic bond (either alpha or beta) connecting a particular pair of sugar units in a particular way. In some cases other sugar units attached as side chains to the polysaccharide interfere with the action of the enzyme. Some enzymes can split either the bonds connecting the terminal sugar unit to the chain or the bonds between units in the interior of the chain; they cannot break both. Polysaccharides can also be degraded by treatment with strong acids at the temperature of boiling water, but this method is largely indiscriminate: it attacks all glycosidic bonds.

Of the structural materials of the cell wall cellulose is the best known and the best understood. It consists entirely of beta-1,4-glucan, that is, of glucose units linked by beta glycosidic bonds between the first and the fourth carbon atoms. The glucan chains are linear, and in the primary wall they aggregate to form fibers made up of about 40 chains each. It is these fibers that are primarily responsible for the strength of the cell wall.

The glucan chains in the cellulose fiber are held together by hydrogen



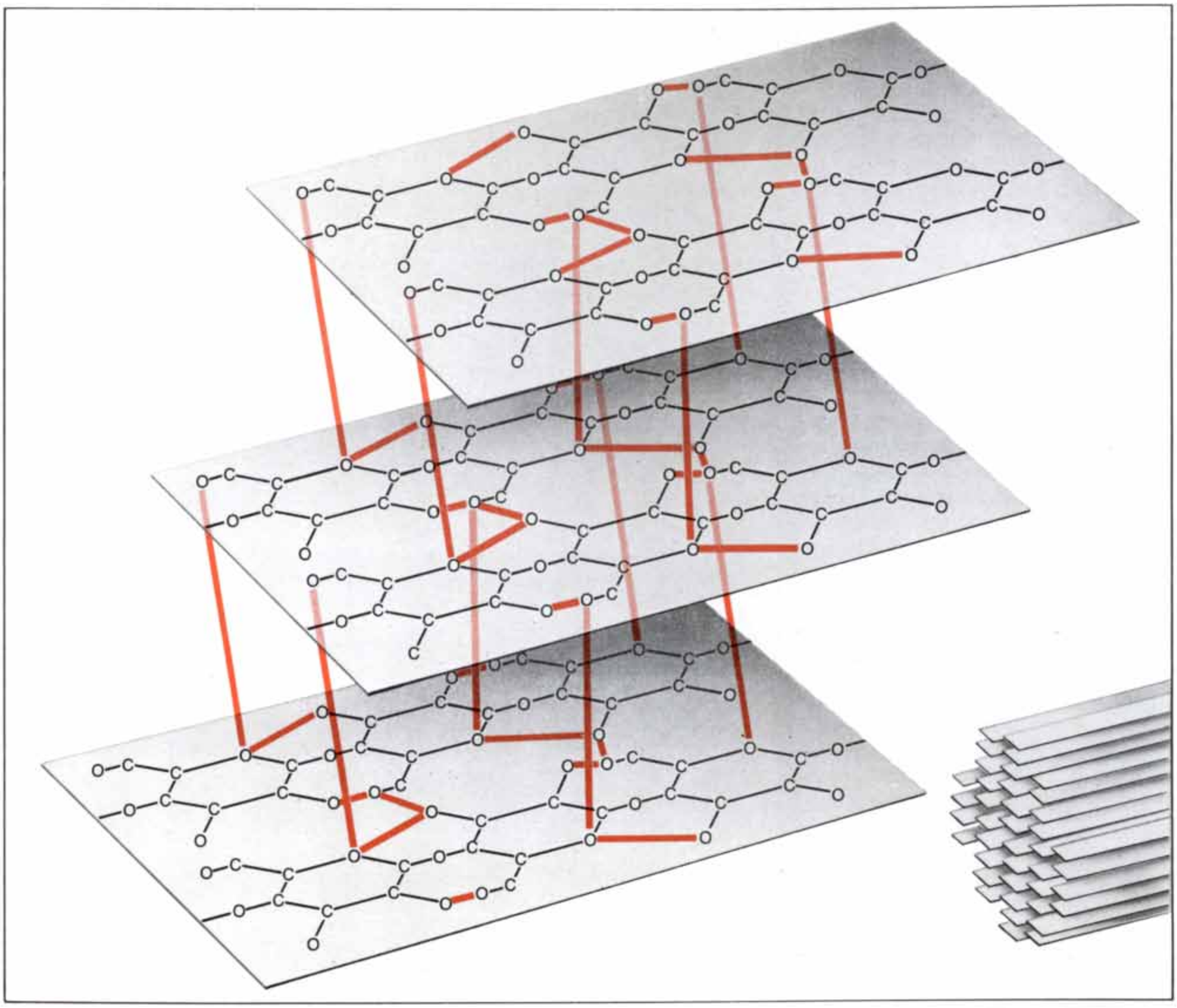

**EIGHT MONOSACCHARIDES found in the primary cell walls of the sycamore tree are depicted schematically, with the ring compressed into a single plane. Glucose, galactose and mannose are stereoisomers; they differ only in the orientation of the chemical groups attached to their carbon atoms. Fucose and rhamnose lack a hydroxyl group on the sixth carbon atom, and galacturonic acid has a carboxyl group (–COOH) at that position. Xylose and arabinose have only five carbon atoms whereas the other sugars have six. In the cell-wall polysaccharides arabinose also differs in that its ring has five members instead of six.**

bonds. These bonds form between the hydrogen atom of a hydroxyl group on one sugar unit and an oxygen atom on another unit. Individually hydrogen bonds are rather weak, but between the glucan chains of a cellulose fiber there are a great many of them.

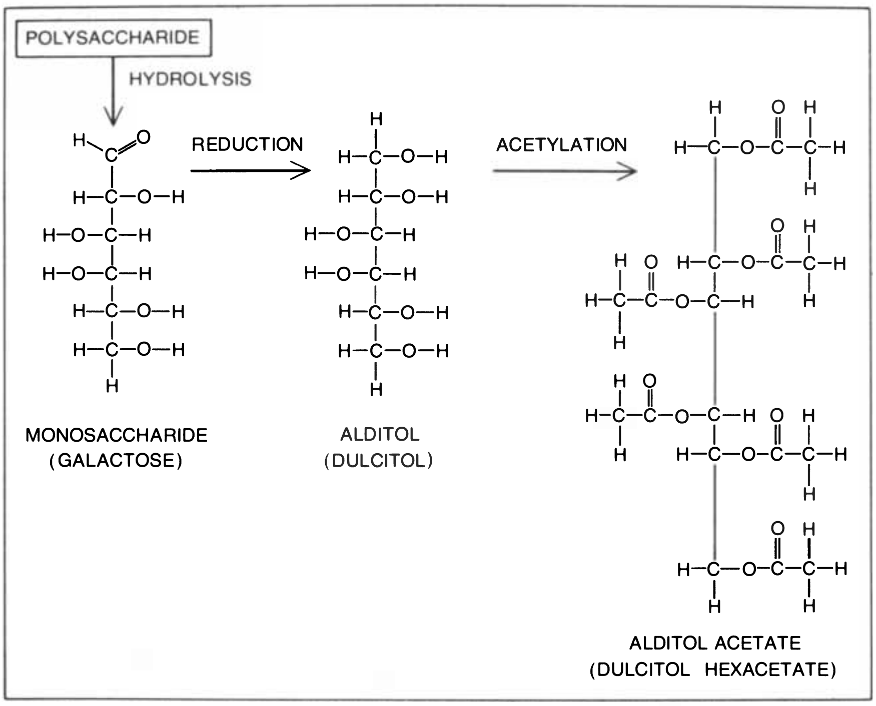
Although cellulose has been studied for more than a century, the internal geometry of the fiber is not yet established with certainty. The structure is orderly enough for the fiber to be regarded as a crystal, and the techniques of crystallography, including the study of X-ray-diffraction patterns, have been applied to its investigation. The results, however, remain slightly ambiguous.

Anatole Sarko and Reto Muggli of the State University of New York at Syracuse have recently presented strong evidence that the glucan chains all run in the same direction, that is, the reducing ends of all the chains are at the same end of the fiber. They also propose that the chains are arranged in such a way that the glucose units are staggered, each being displaced one-half the length of a single glucose unit in relation to the adjacent strand [*see illustration below*]. In their model of the fiber each glucan strand is linked to other strands by two hydrogen bonds for each glucose unit.

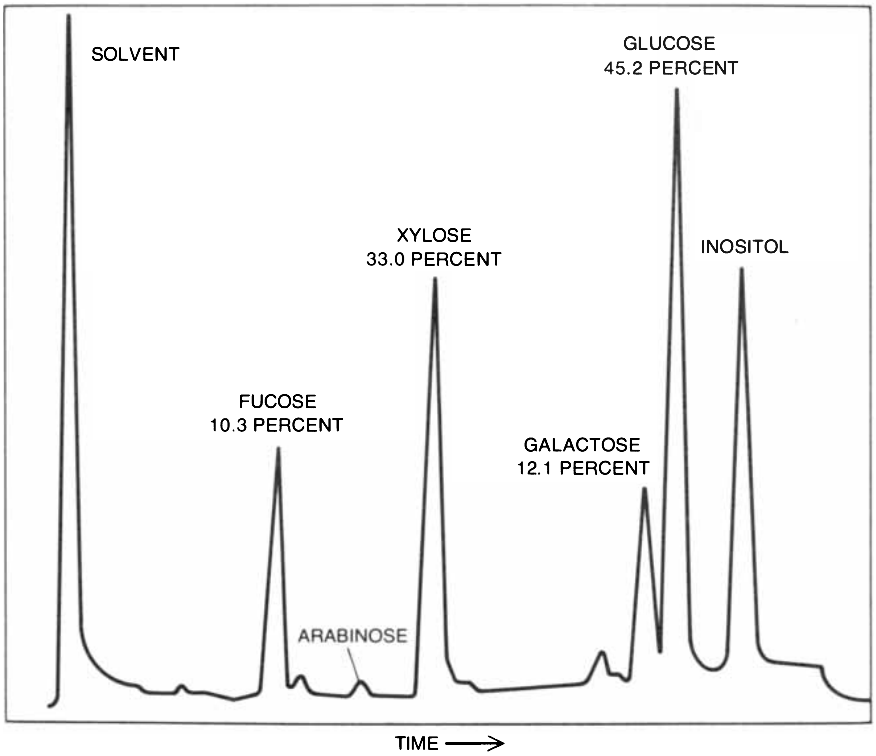
The large number of hydrogen bonds between glucan chains makes the cellulose fiber an extremely cohesive structure. When it is attacked chemically, the covalent glycosidic bonds between glucose units frequently break before the chains can be separated. Even enzymes specific for the bond in the glucan chain are not very effective in degrading the intact cellulose fiber. Because the chains are packed tightly together enzyme molecules cannot approach the susceptible glycosidic bond. Of course, cellulose



**CELLULOSE is made up entirely of glucose units linked together in long chains. In a cellulose fiber there are about 40 of these chains, called glucan, in an orderly array (*diagram at lower right*). The glucan chains are straight, and they line up next to one another to form sheets. The chains also line up one above the other, but in this dimension they are staggered at half the length of a single glucose unit. Within a glucan chain the units are joined by glycosidic bonds in the beta configuration, and each unit is upside down with respect to the preceding one. The chains are held together by hydrogen bonds (*colored lines*) between oxygen atoms and the hydrogen atoms of hydroxyl groups. (In this diagram the hydrogen atoms are not shown; the bonds are indicated as if they extended from one oxygen atom to another. In addition the lengths and angles of the bonds are distorted because the sugar units have been flattened and the chains separated for clarity.) It is the large number of hydrogen bonds that gives cellulose its strength and resistance to chemical degradation. This model of the cellulose fiber is based on an analysis performed by Anatole Sarko and Reto Muggli of the State University of New York at Syracuse. Several of its features, including the pattern of hydrogen bonding, remain tentative.**




**CHEMICAL ANALYSIS** of the cell-wall polysaccharides begins with the conversion of sugars to volatile derivatives. The polysaccharide is degraded by acid hydrolysis to liberate its monosaccharide constituents; one of these, galactose, is shown. The monosaccharide is then converted to an alditol (a sugar-derived alcohol) by reducing the aldehyde group to yield a hydroxyl group. The alditol derived from galactose is called dulcitol. Finally, acetyl groups ($-COCH_3$) are bonded to all six of the alditol's hydroxyl groups. The resulting alditol acetates are volatile and can be separated and identified by gas chromatography.




**COMPOSITION** of the cell-wall polysaccharide xyloglucan was revealed by gas chromatography. Alditol acetates derived from xyloglucan were injected into the chromatograph, where they were vaporized and flushed through a column containing an adsorbent liquid. Each alditol acetate migrated through the column at a different rate and when detected at the end of the column produced a separate peak on the graph. The proportion of each component was determined from the area under the peak. Inositol was added as a standard.

can eventually be broken down by enzymes (if it could not, dead plants would never decay), but the degradation is always slow.

Cellulose fibers make up only a part of the primary cell wall. They are embedded in a matrix of other molecules, most of which are also polysaccharides. In the cell walls my colleagues and I have examined most closely there are three (in addition to cellulose): xyloglucan, arabinogalactan and rhamnogalacturonan. They are named for their principal monosaccharide constituents. Xyloglucan consists mainly of xylose and glucose, although it contains small amounts of other sugars as well. Arabinogalactan is made up of arabinose and galactose, and rhamnogalacturonan contains rhamnose and galacturonic acid.

The chemistry of these polysaccharides is considerably more complex than that of cellulose. In cellulose all the sugar units are identical, and they are all bonded to one another in the same way. In the other polysaccharides there are two or more kinds of sugar unit, connected by several kinds of glycosidic linkage. Just two molecules of a six-carbon sugar, such as glucose, can be joined in 11 distinct ways, and three different sugar molecules can be arranged in more than 1,000 ways. Since a single polysaccharide molecule can consist of hundreds of sugar units, the potential complexity is enormous.

Fortunately for us, in the actual molecules of the cell wall we have encountered only about two dozen kinds of glycosidic bond. Moreover, all the polysaccharides in the primary wall have been found to consist of relatively small repeating substructures; the largest of these substructures has 10 sugar units. If it can be determined how the substructures are put together, the entire molecule can be described.

The materials of the cell wall have been characterized now only because analytical techniques developed in recent years have enabled us and other investigators to isolate and identify molecules that differ only in such subtle features as the position or orientation of a single hydroxyl group. One of the most important techniques is gas chromatography, in which gaseous molecules are passed through a long tube, or "column," containing an adsorptive liquid. The rate at which a substance migrates through the column depends on its solubility and volatility, and a mixture of substances can therefore be sorted into fractions according to their properties. The mass spectrometer is another valu-

# Western Electric Reports:

## An inside look at crystal growth.

Engineers at Western Electric's Engineering Research Center have developed an improved method for controlling the growth of the crystals used in light emitting diodes (LED's). The new technique represents one more step toward low-cost, mass produced LED's.

LED's have found many uses in telecommunications equipment as illuminators, indicator lamps and numeric displays. They consume very little power and last from 10 to 100 times longer than the devices they replace.

LED's used in the Bell System are made from gallium phosphide (GaP) single crystals. Economical processing using standard-sized fixtures requires crystals of uniform diameter. But because GaP single crystals must be grown inside a high pressure vessel, monitoring and controlling crystal growth has been a problem.

Previously, crystal growth could only be monitored visually. The halo surrounding the growing crystal was observed through closed circuit television. Since the halo would expand and contract with the diameter of the growing crystal, it provided some measure of control. But phosphorous vapors condensing on the viewing window partly obscured the halo, making precise control difficult.

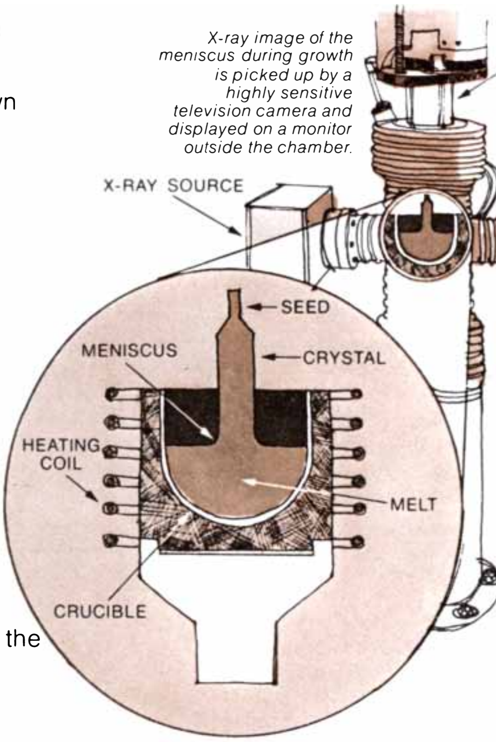
The new monitoring technique is similar to the use of a fluoroscope in medicine. X-ray imaging provides an unobstructed view of the meniscus formed where the solid crystal meets the liquid melt. Western Electric engineers have correlated the height and angle of this meniscus to the crystal's growth condition. This is useful because a change in the shape of the meniscus signals a change in the temperature of the melt *before* it is manifested as a change in the crystal's diameter.

A change of just 4° in the liquid-solid contact angle can be observed, allowing adjustments to be made in either temperature or pulling rate to maintain uniform growth.

X-ray imaging is in production use at Western Electric's plant in Reading, Penn.

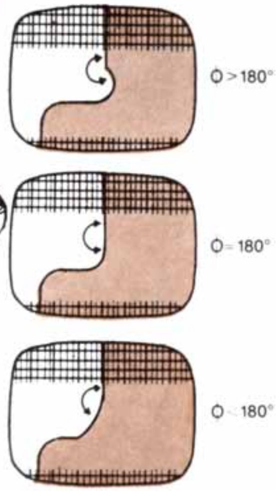
**Benefit:** X-ray imaging of the meniscus of a growing crystal has permitted a marked improvement in the monitoring and control of crystal growth. It helps insure high yields of uniform diameter crystal wafers for processing into LED's.

*Crystals of uneven diameter are difficult to process economically and efficiently. X-ray imaging now yields crystals of a diameter within a tolerance of ± 1/16 inch.*




*X-ray image of the meniscus during growth is picked up by a highly sensitive television camera and displayed on a monitor outside the chamber.*

*Growing crystals: seed is dipped into crucible of molten GaP, maintained just above melting temperature. It is rotated and withdrawn at controlled rate, producing cylindrical crystal*

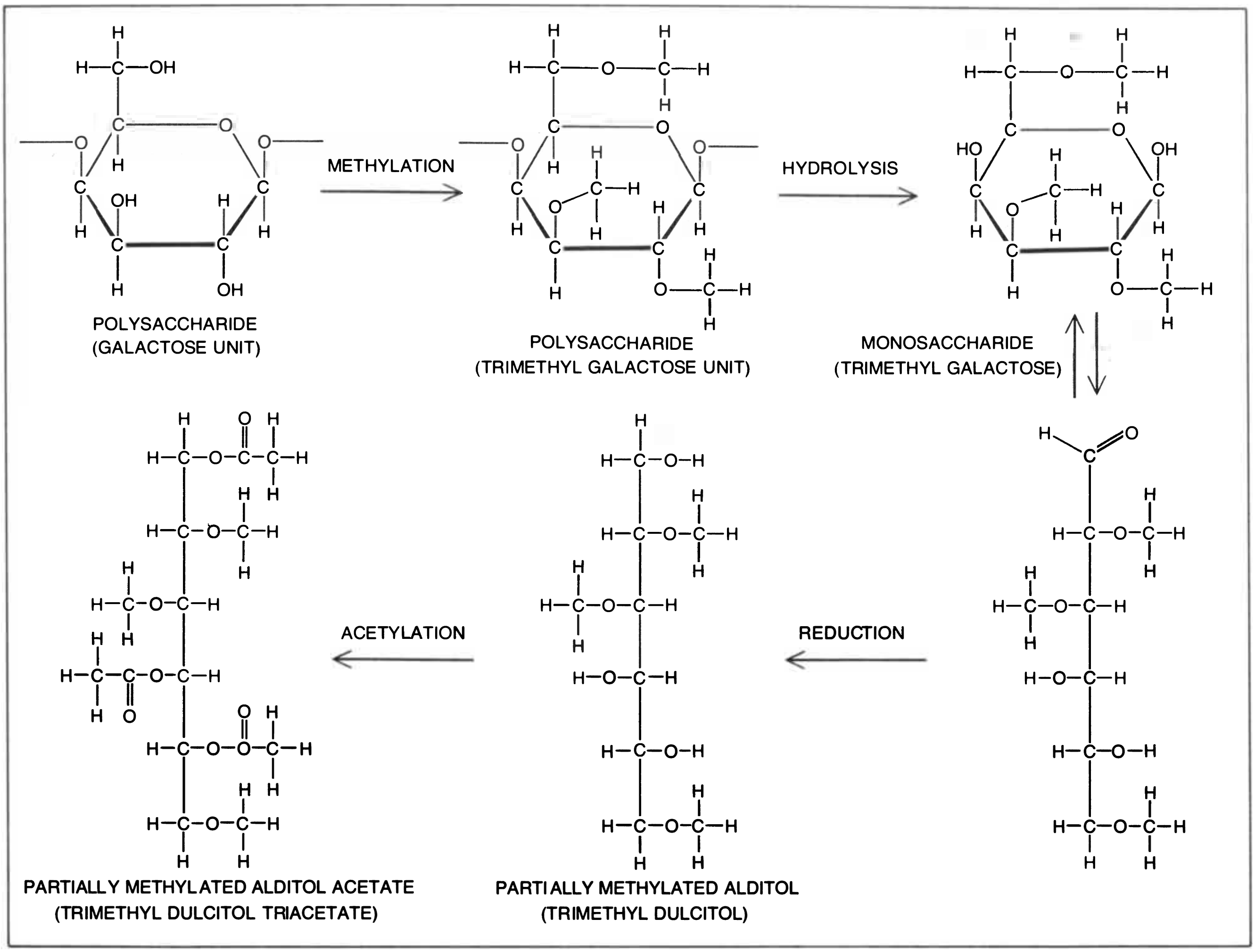



THE LIQUID-SOLID CONTACT ANGLES

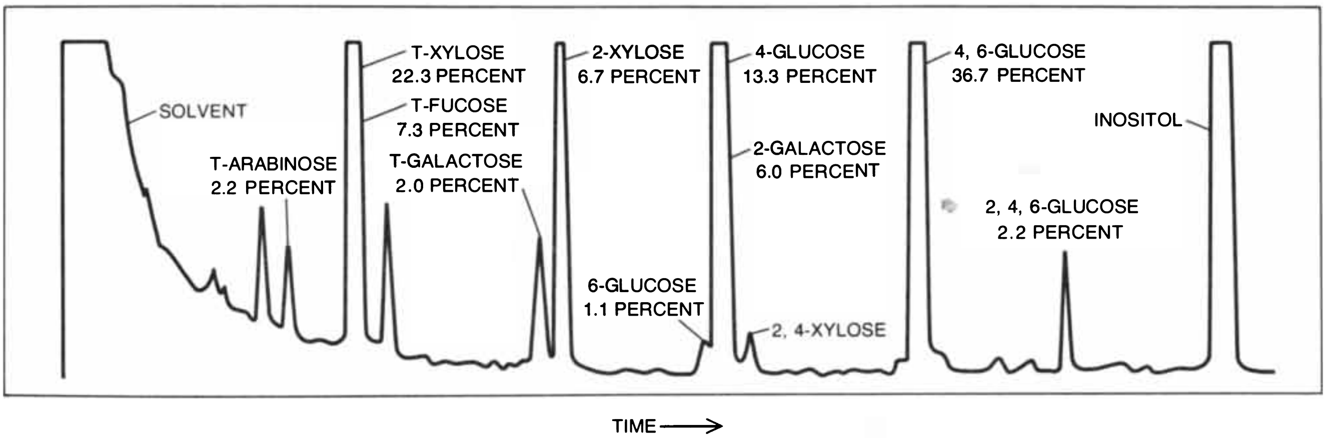
*X-ray image of the meniscus at various temperatures. The smaller the angle, the lower the temperature. The larger the angle, the higher the temperature. An angle of 180° indicates the desired "steady state" growth condition.*

**Western Electric**

**We make things that bring people closer.**




**STRUCTURAL ANALYSIS** of a polysaccharide requires knowledge of how each sugar unit is bonded to adjacent units. This information is obtained by a technique that attaches methyl groups ($-CH_3$) to all the hydroxyl groups that are exposed in the polysaccharide. Where the sugar is linked to another unit the hydroxyl group is absent, so that at those positions the molecule is not methylated. The polysaccharide is then hydrolyzed and the free monosaccharides are reduced and acetylated by the same methods employed in the determination of wall composition. The resulting molecules have acetyl groups only where in the polysaccharide they were bonded to other sugars (and at the ring-forming oxygen atom); the remaining positions are occupied by methyl groups.




**BONDING OF MONOSACCHARIDES** in xyloglucan was analyzed by gas chromatography of partially methylated alditol acetates. The molecules were sorted by the type of sugar and by the location of acetyl groups; the acetyl groups also denote where the molecule was linked to others in the polysaccharide. Sugars prefixed by *T* were terminal units; *T*-xylose, for example, was bonded through its first carbon atom but had no other sugar units attached to it. More complex bonding patterns are indicated numerically; 4,6-glucose, for example, was linked to sugars at the fourth and sixth carbon atoms as well as at the first. Some peaks represent more than one sugar, and some constituents are not identified. Percentages give the proportion of each molecular species in the polysaccharide.

able analytic tool: it provides a means of sorting and identifying substances that are chemically similar. In this device the molecules are fragmented and ionized and passed through a magnetic field. The identity of the ions can be deduced from the angle through which they are deflected by the field. We have found it convenient to employ both techniques in concert by passing the effluent of a gas chromatograph directly into a mass spectrometer. The data obtained are compiled and analyzed by computer.

Even with techniques such as these the analysis of polysaccharides remains difficult. The approach required is somewhat like the one employed in doing a jigsaw puzzle, except that in this case there were three puzzles to be solved simultaneously. When a fragment of a molecule became available for study, we had first to discover which of the three polysaccharides it belonged to and then to determine where it fit into the chosen molecule.

In investigating the cell wall the first requirement is a quantity of cells with walls of uniform structure. Ordinary plant tissues will not do; stems, leaves and roots all contain several kinds of cells in various stages of development, some of which have primary walls and some secondary walls. We obtained uniform material by growing cells in suspension in a culture medium. Under such conditions the cells divide and grow continuously, and all of them therefore have primary walls. Most of our work was done with suspension-cultured cells of the sycamore tree.

We initially approached the problem of structure through an analysis of composition, that is, by determining what monosaccharides the wall contains and in what proportions they are present. First the walls are separated from other portions of the cell, then soluble components of the wall, which are not part of the structure itself, are washed out. The remaining material is treated with acids or degradative enzymes in order to decompose the polysaccharides; this procedure also serves to isolate the cellulose, since cellulose is resistant to degradation. The resulting solution contains all the sugar units that had been incorporated in the structure of the cell wall with the exception of the glucose that remains bound in cellulose fibers. The cellulose is assayed separately.

The monosaccharides isolated from the wall cannot be analyzed directly by gas chromatography because they are not volatile; if they are heated, they do not boil to give rise to gases but instead decompose. The monosaccharides are therefore converted to volatile sugar derivatives before analysis. The oxygen in the aldehyde group of each sugar is first reduced, yielding a hydroxyl group and converting the sugar to an alcohol; alcohols derived from these sugars are called alditols. All the hydroxyl groups on the molecule are then reacted with acetyl groups, and the molecule becomes an alditol acetate [*see top illustration on page 86*]. The alditol acetates derived from monosaccharides are volatile, and they are readily separated by gas chromatography.

By this method we determined that the primary wall of sycamore cells is made up of just eight monosaccharides. From the chromatogram we also calculated the quantity of each sugar extracted from the wall. Arabinose accounts for 28.2 percent of the cell wall, galactose for 14.5 percent, galacturonic acid for 13.2 percent and xylose for 10.2 percent. Rhamnose and fucose are present in considerably smaller quantities, and there is a trace of mannose. Finally, the glucose units incorporated in cellulose fibers make up 24 percent of the wall carbohydrates, and there is another 4.2 percent of glucose in polysaccharides other than cellulose.

Knowing the composition of the wall provides a preliminary test for hypotheses about its structure; they must not contradict the observed relative abundance of each sugar. Information about the composition alone, however, cannot reveal how the sugar units are linked together in the polysaccharides. One must know for each sugar unit which of the five or six carbon atoms participate in glycosidic bonds, and for the first carbon whether the bonds are made in the alpha or in the beta configuration. This information can also be obtained by gas chromatography, but a more elaborate procedure is required.

Before the polysaccharides are decomposed they are treated chemically so that the hydrogen atom of each of the free hydroxyl groups is replaced by a methyl group ($-CH_3$). A convenient method for accomplishing the methylation was developed in 1966 by Sen-itiroh Hakomori of the University of Washington. The methylated polysaccharides are then degraded (by acids) to yield partially methylated monosaccharides. These sugars have hydroxyl groups at those positions where in the polysaccharide they had been bonded by glycosidic linkages to other sugar units and at the oxygen atom that had been part of the ring structure; all the hydroxyl groups that had been free in the polysaccharide have been methylated. The sugars are then reduced and acetylated to produce partially methylated alditol acetates. The procedure for this step, which was devised by Bengt Lindberg and his colleagues at the University of Stockholm, is similar to the one employed in determining the composition of the polysaccharides [*see top illustration on opposite page*].

When these compounds are separated by gas chromatography and further characterized by mass spectrometry, the nature of the bonds that connected each sugar unit in the polysaccharide can be determined. The absence of a methyl group and the presence of an acetyl group on a carbon atom indicates that another sugar unit had been bonded to the molecule at that position. Glucose that had had another sugar attached to it at the fourth carbon atom, for example, can be distinguished from glucose that had been bonded at the sixth carbon, and both of these molecules can be distinguished from glucose that had been bonded at both the fourth and the sixth positions. The quantity of each sugar in each bonding formation can also be determined [*see bottom illustration on opposite page*].

Knowing the sugars present in the wall and the nature of the bonds associated with each of them, we endeavored to build up models of the cell-wall materials. We began by breaking the polysaccharides into oligosaccharides: fragments of a few sugar units each. The structure of the fragments was then determined, and finally the fragments were fitted together to depict the entire polysaccharide.

An oligosaccharide can be meaningfully analyzed only if each of the enzymes employed to fragment the wall polymers is specific for a single glycosidic bond. In fact, a variety of enzymes is required, so that many different fragments can be produced. The enzymes are obtained from bacteria and fungi that are pathogens of plants. The microorganisms employ the enzymes to break down cell walls in order to gain access to the plant cells; when the fungi or bacteria are grown in culture, the enzymes are secreted into the medium, and they can then be extracted and purified. Treatment with such enzymes ensures that only one kind of bond will be broken, but it also ensures that virtually all bonds of this type will be destroyed.

The delicacy of the technique can

best be illustrated by an example: the analysis of the structure of xyloglucan. The polysaccharide was treated with an endoglucanase, an enzyme derived from the fungus *Trichoderma viride*. The endoglucanase acts on glycosidic bonds in the beta configuration that connect one glucose unit to another. It is active only on bonds connected to the fourth carbon atom; it does not affect glucose units that have a sugar attached at both the fourth position and the sixth.

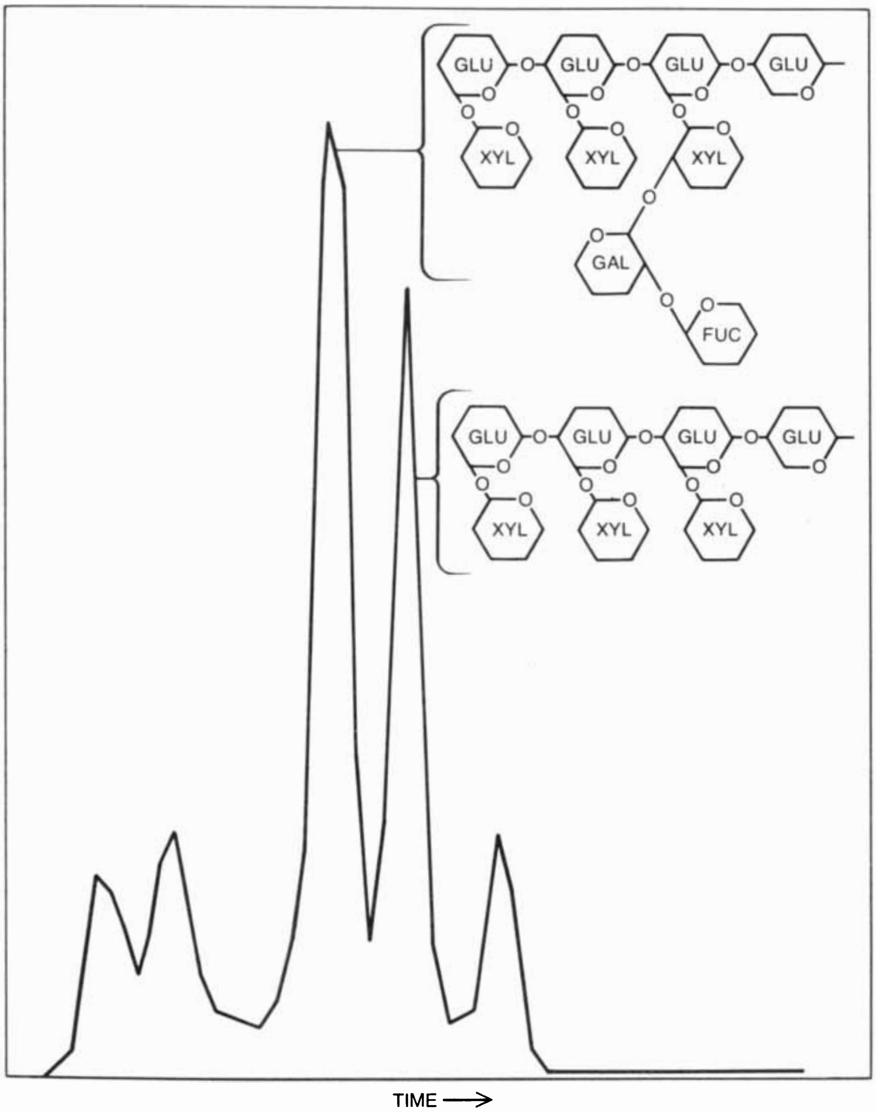
Xyloglucan treated with this endoglucanase splits into two kinds of fragments, one with seven sugar units and the other with nine. They were separated by gel filtration, a technique that distinguishes between molecules on the basis of their size [*see illustration below*]. The fragments were then analyzed by methylation, acetylation and gas chromatography. The seven-unit fragment was found to consist of four units of glucose and three units of xylose. The nine-unit fragment had the same constituents as the smaller one, with the addition of one unit each of fucose and galactose.

From an analysis of the possible bonding arrangements of these monosaccharides we were able to deduce that the backbone of both fragments consists of four units of glucose linked linearly by beta bonds between the first and the fourth carbon atoms, just as in the glucan chains of cellulose. The three xylose units are bonded to the sixth carbon atom of three of the glucose units; since we knew that the enzyme is ineffective where a sugar is attached at that position, we were able to conclude that it must be the glucose nearest the enzyme-broken bond that lacks a xylose side chain. The position of the galactose and fucose units in the larger fragment was determined by treatment with other enzymes. The galactose is attached to one of the xylose units, and the fucose is attached to the galactose. There is in addition a third, small fragment, and when it is rejoined to the seven-unit and nine-unit fragments where the endoglucanase split them, the structure of the xyloglucan molecule is complete [*see top illustration on opposite page*].

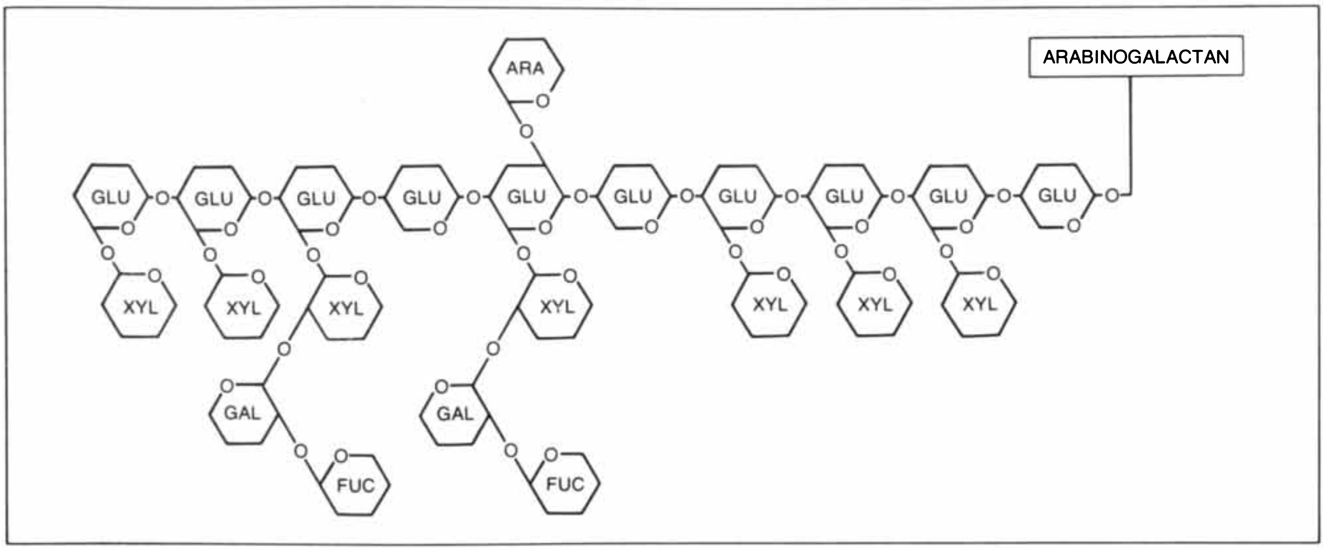
Arabinogalactan and rhamnogalacturonan were deciphered in much the same way, although of course different enzymes were required. Arabinogalactan appears to consist of a series of arabinose units linked at one end to a series of galactose units. Some of the arabinose units and one or more galactose units are attached as side chains [*see middle illustration on opposite page*]. Rhamnogalacturonan is made up mainly of galacturonic acid linked in unbranched sequences. Every eight to 12 units in the chain there is a rhamnose unit, followed by a single galacturonic acid unit and another rhamnose. The rhamnose units are bonded in such a way that each one puts a kink in the otherwise linear chain [*see bottom illustration on opposite page*].

When the cell-wall polymers are degraded with certain enzymes, some of the liberated oligosaccharides contain fragments of more than one polysaccharide. Such fragments indicate that in the cell wall the polysaccharides (excluding cellulose) are bonded covalently to one another. Such composite fragments have also enabled us to determine how the molecules are connected, and they have thus given us a glimpse of the geometry of the polymers. From information of this kind W. Dietz Bauer, Kenneth Keegstra, Kenneth Talmadge and I have formulated a model of the chemical structure of the primary walls of sycamore cells [*see illustration on page 92*].

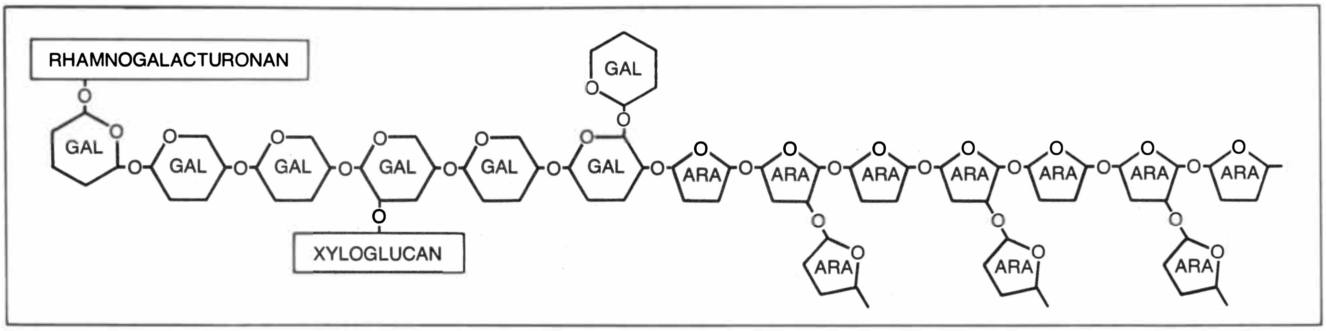
In our model each cellulose fiber is completely coated with a layer of xyloglucan one molecule thick. The multiple glucose units of the xyloglucan lie parallel to the axis of the fiber, and they are



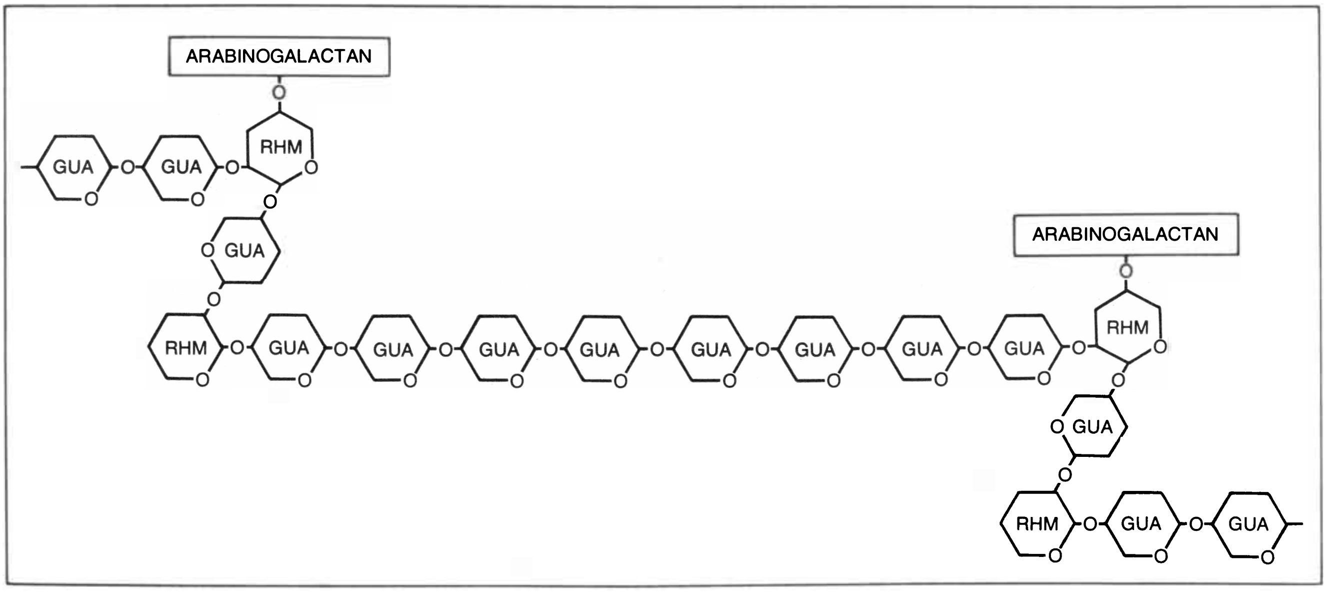

**FRAGMENTS of xyloglucan were separated by gel filtration, which distinguishes between molecules on the basis of their size. Large molecules wash through the gel quicker than smaller ones. The fragments were produced by cleaving xyloglucan with an enzyme that splits apart glucose units bonded at the first and fourth carbon atoms but not at the sixth. The fragments shown can be assembled, with a minor addition, to form a xyloglucan molecule. The three smaller peaks represent other fragments. The monosaccharide units that make up the fragments are glucose (*GLU*), xylose (*XYL*), galactose (*GAL*) and fucose (*FUC*).**




**XYLOGLUCAN** is constructed on a backbone of glucose units (*GLU*) linked in the same way they are in cellulose. Xylose units (*XYL*) are attached to this backbone, and galactose (*GAL*) and fucose (*FUC*) are bonded to the xylose. Arabinose (*ARA*) is a minor constituent. Glucose units form hydrogen bonds to cellulose, and one end of the xyloglucan chain is bonded to arabinogalactan.




**ARABINOGALACTAN** is believed to consist of a chain of arabinose (*ARA*) appended to another chain of galactose (*GAL*). The relatively few side chains are known to have only a single sugar unit each but their exact location has not been ascertained. Xyloglucan bonds to an interior galactose unit, and the reducing end of the arabinogalactan molecule is attached to rhamnogalacturonan.



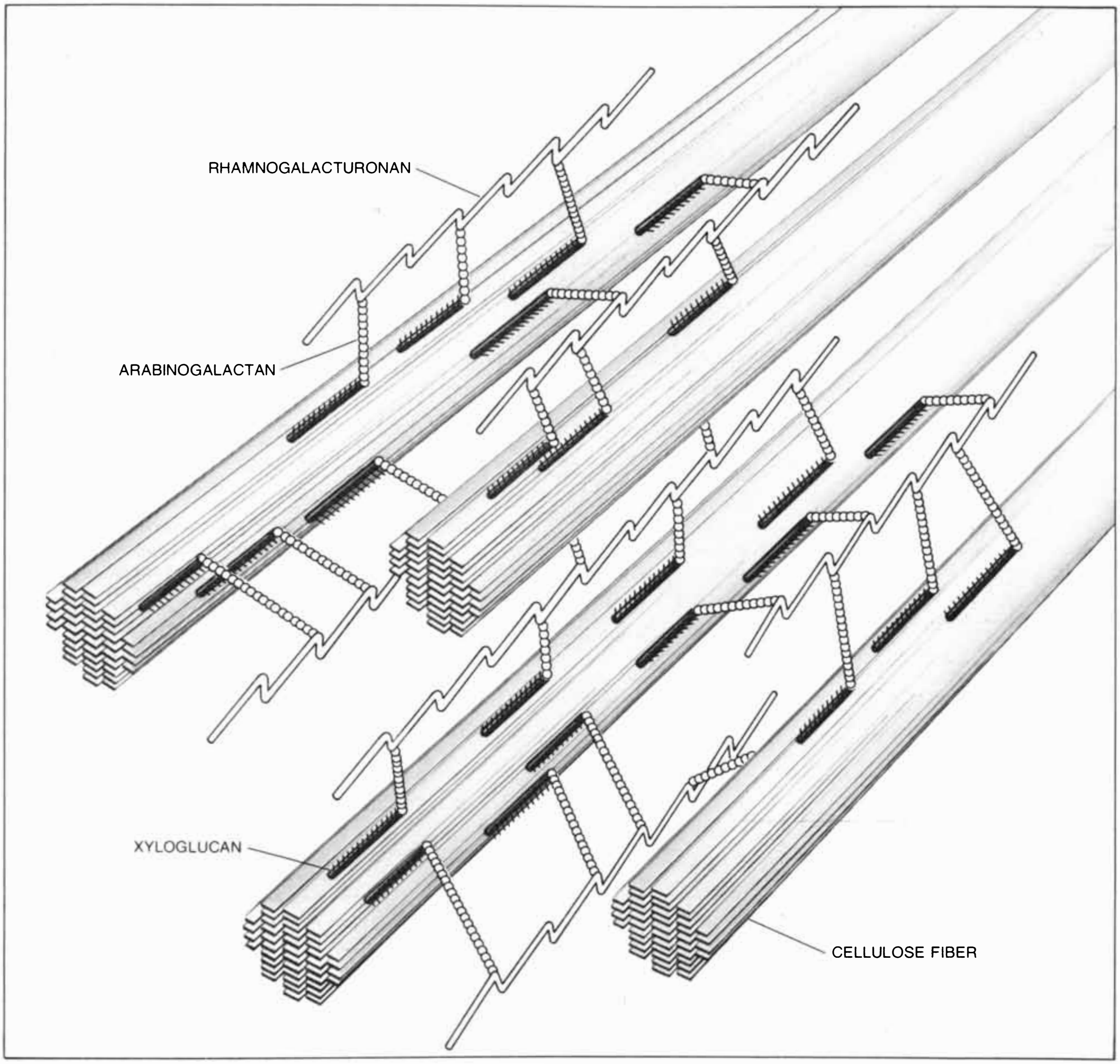

**RHAMNOGALACTURONAN** is a straight polysaccharide interrupted by kinks. Straight sequences consist of galacturonic acid (*GUA*); the kinks are produced by rhamnose (*RHM*). Half of the rhamnose units have an arabinogalactan molecule bonded to them.

hydrogen-bonded to the glucan chains in the fiber. Hydrogen-bonding appears to be feasible because the glucose portions of xyloglucan are structurally identical with the glucan chains of cellulose. Unlike the glucan, however, xyloglucan can form hydrogen bonds on one side only; bonding is impeded on the opposite side by the protruding fucose and galactose units.

At its reducing end each xyloglucan molecule is glycosidically bonded to an arabinogalactan molecule. Although the exact geometric relations are not yet known, the arabinogalactan chains can be thought of as running radially away from the cellulose fiber, like spokes radiating from a hub. The galactose unit at the reducing end of arabinogalactan is linked glycosidically to rhamnogalacturonan. The arabinogalactan is believed to bond exclusively to rhamnose units, the sugars that give rise to kinks in the rhamnogalacturonan chain.

Each cellulose fiber is coated with many xyloglucan molecules. Each xyloglucan is bonded to only one arabinogalactan, and each arabinogalactan terminates at one rhamnogalacturonan chain. The rhamnogalacturonan chains, however, receive numerous arabinogalactan molecules, including chains radiating from more than one cellulose fiber. Rhamnogalacturonan thus binds the fibers into a more or less rigid matrix.

The protein component of the wall may also have a structural function. There are sugars attached to it, and there is some evidence that rhamnogalacturonan molecules bind to these sugars. Since the structural role of the protein has not been established, however,




**MODEL OF THE CELL WALL** devised by the author and his colleagues assumes that cellulose fibers are linked together by three other polysaccharides. Many xyloglucan molecules adhere to the surface of the fibers. Each xyloglucan molecule binds to a single arabinogalactan chain, which in turn binds to a single rhamnogalacturonan molecule. Each rhamnogalacturonan chain can receive several arabinogalactan molecules, radiating from different cellulose fibers. Similarly, each cellulose fiber can be connected to several rhamnogalacturonan chains. As a result of this extensive cross-linking the fibers are immobilized in a seemingly rigid matrix.

# The Trans-Alaska Pipeline.

## A report on the most remarkable private construction project in American history.

Far above the Arctic Circle on Alaska's North Slope lies the largest oil field in North America. The Prudhoe Bay oil field holds an estimated 10 billion barrels (one barrel equals 42 gallons) of crude oil.

For years engineers have generally agreed that a pipeline would be the most economical way to get the oil out of this wilderness.

In 1974 work began on the Trans-Alaska Pipeline System—the largest single construction project ever undertaken by private industry.

*It took over one-half million tons of steel to make the 798 miles of pipe for the project. The sections are 40' and 60' long, 48" in diameter.*

**The route**

The Trans-Alaska Pipeline System will be about 798 miles long—winding its way from Prudhoe across the rugged face of Alaska to Valdez, a deep-water port in southern Alaska.

The Pipeline must cross 3 major mountain ranges, including the Brooks Range, where it will snake through Dietrich Pass at 4,500 feet


*The 798-mile Trans-Alaska Pipeline System may ultimately carry 2 million barrels of oil a day from Prudhoe Bay to Valdez.*

elevation. It will cross 17 major rivers, including the Yukon, third largest in North America.

At the southern terminal point in Valdez, the oil will be loaded into ocean-going tankers and shipped to the U.S. West Coast.

**80° below zero**

Working conditions along the route are almost without parallel in the history of the industry. 40-mile-an-hour winds and temperatures down to 80° below zero can reduce human work efficiency by 90 percent.

**27 Empire State Buildings**

It will take over three years and nearly $6 *billion* to build the Pipeline. This is the equivalent of what it would cost today to build 27 Empire State Buildings, or 3 Panama Canals.

Ownership of the Pipeline is held by eight companies, with Exxon Pipeline Co. having a 20 percent interest. These companies formed *Alyeska Pipeline Service Co.* to design and construct the Pipeline.

**What's happening today**

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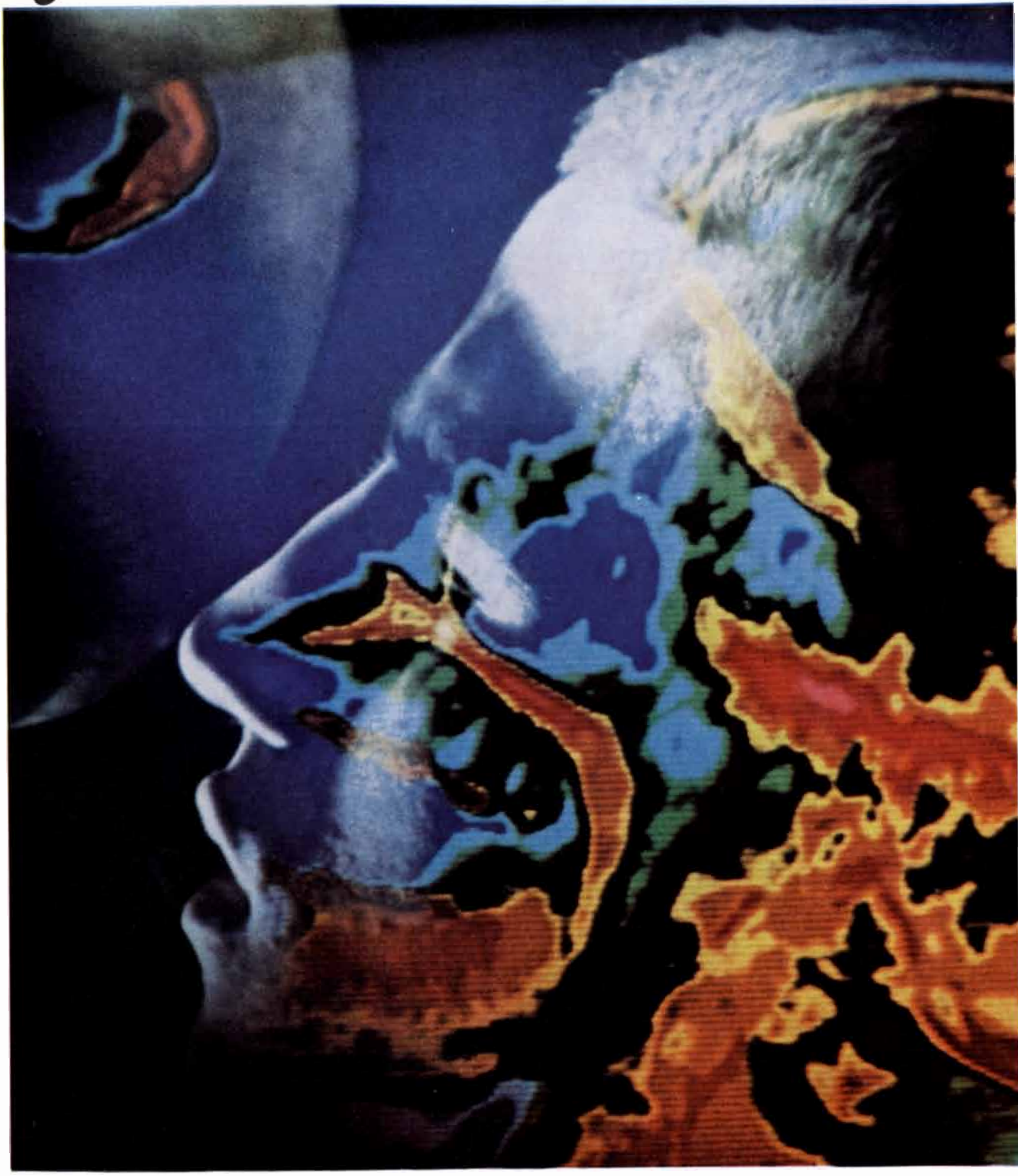

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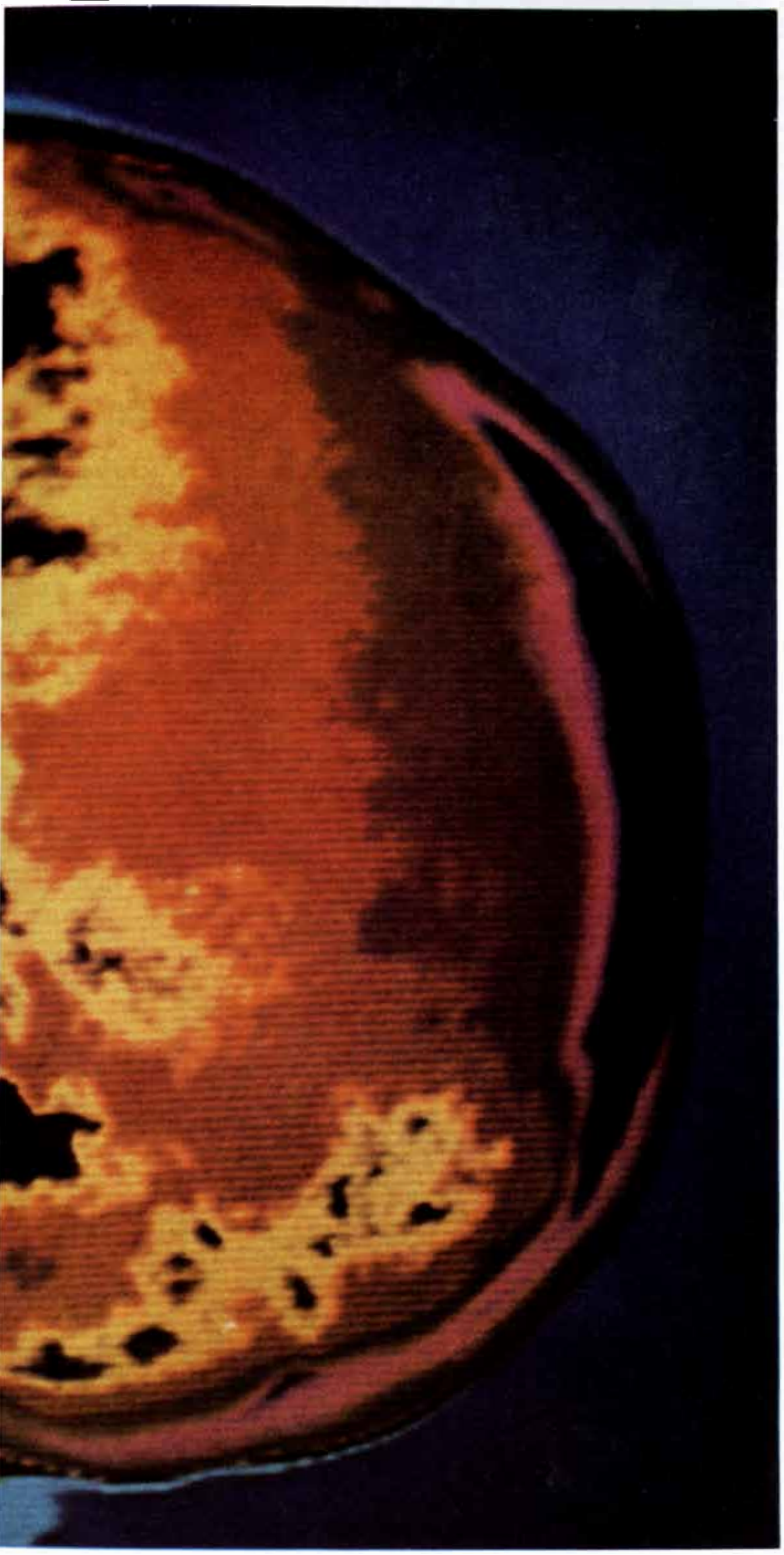

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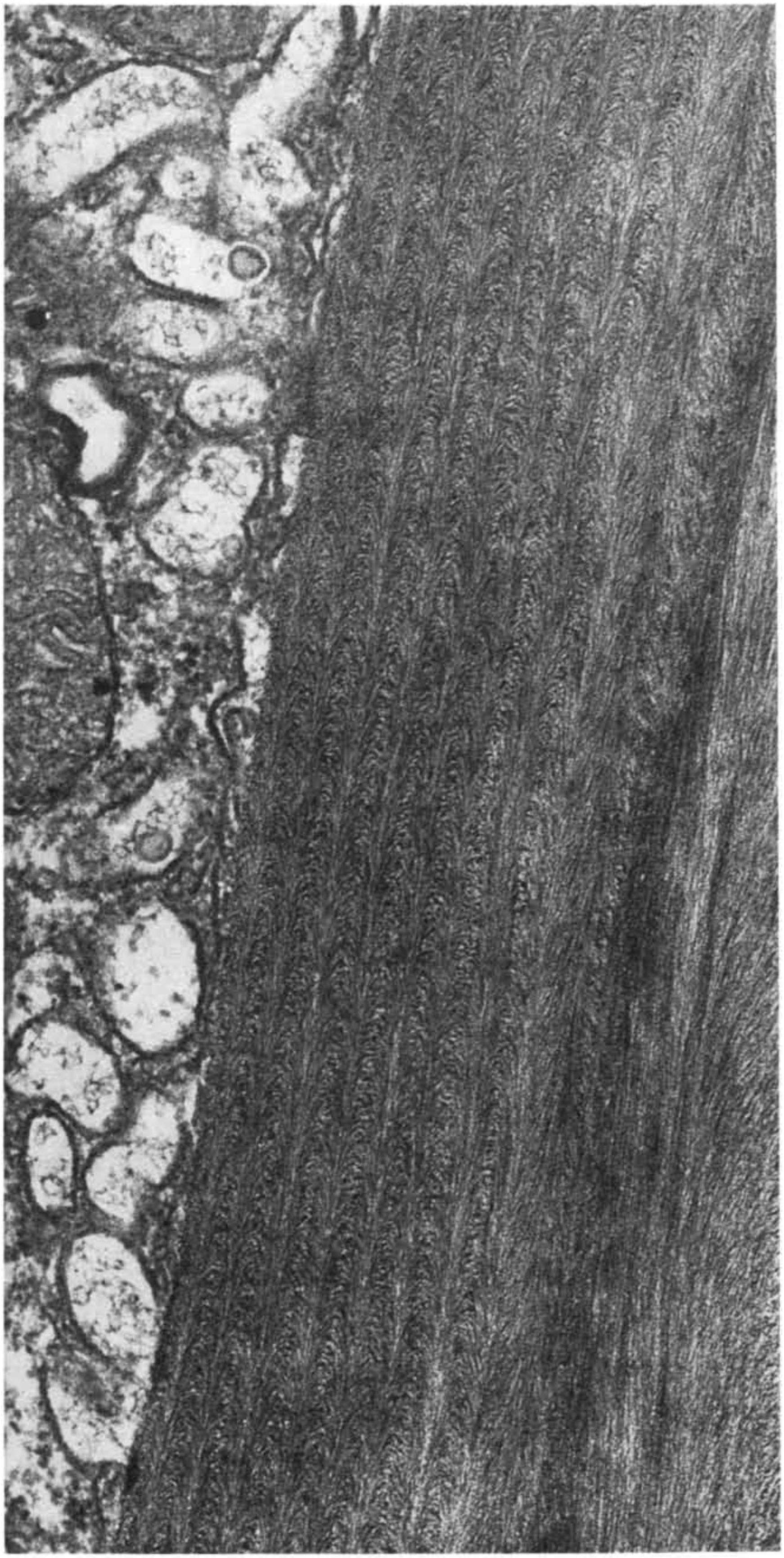
and since a coherent model of the wall can be formulated without it, we have ignored it in our proposed structure.

Our model predicts that a cross section of the primary wall will show between 10 and 50 cellulose fibers, interconnected by the other three structural polysaccharides. If the fibers are lined up in a parallel array, as they appear to be in cells that have fully elongated, a basic structural unit should repeat across the width of the cell, once for each fiber. Electron micrographs made by Eldon H. Newcomb and his colleagues at the University of Wisconsin display repeating structures that have approximately the expected dimensions in the primary cell walls of several plants [*see illustration at right*]. It is not yet known whether or not the structures visible in the micrographs are equivalent to the chemical structures predicted by our model.

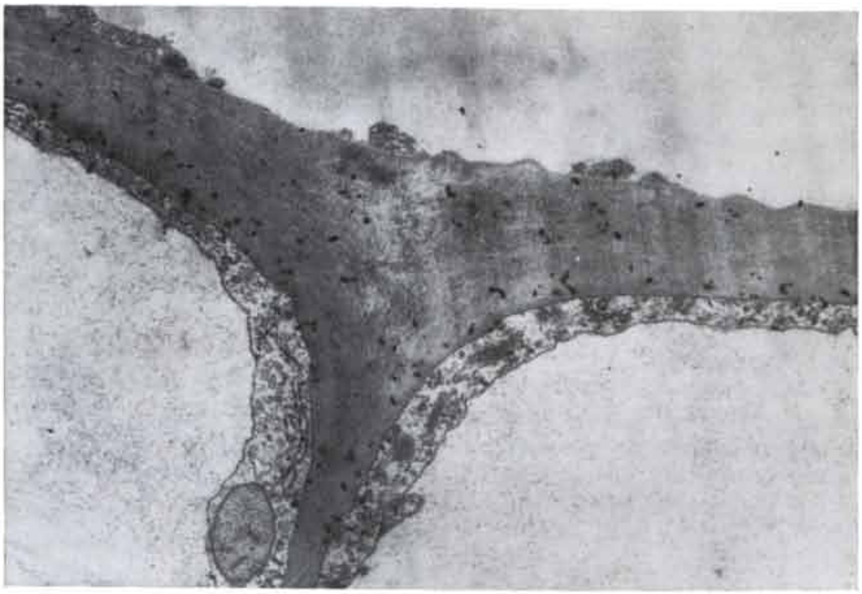
Our model was derived entirely from experiments with sycamore cells cultured in suspension, but it now appears that it is valid for other kinds of cell as well. The structure of the wall polysaccharides associated with cells grown in the intact plant instead of in culture has been determined by other investigators by the careful removal of cells with primary walls from branches of sycamore and aspen trees. The molecules observed are very similar to, if not in fact identical with, those found in cultured cells.

The sycamore belongs to the large subclass of plants called dicotyledons, the plants whose embryos have two rudimentary leaves. The primary walls of other plants in the same subclass have been found to have a closely related structure, and it thus appears that the model is valid for all dicotyledons. The red kidney bean, for example, has been investigated by Barry Wilder of the author's laboratory. The plant is only distantly related to the sycamore, but its cell walls are nearly identical.

More recently David Burke, Peter Kaufman, Michael McNeil and I have surveyed the primary wall structure of monocotyledons, plants of a different subclass whose embryos have only one primitive leaf. The plants we investigated were wheat, oats, rice, sugarcane, bromegrass and rye grass. The composition of the walls and the pattern of bonding in these six grasses are quite unlike those of the dicotyledons. The primary cell walls of monocotyledons may nevertheless be constructed according to the same architectural principles. It seems probable that the cellulose fibers are cross-linked by polysaccharides whose



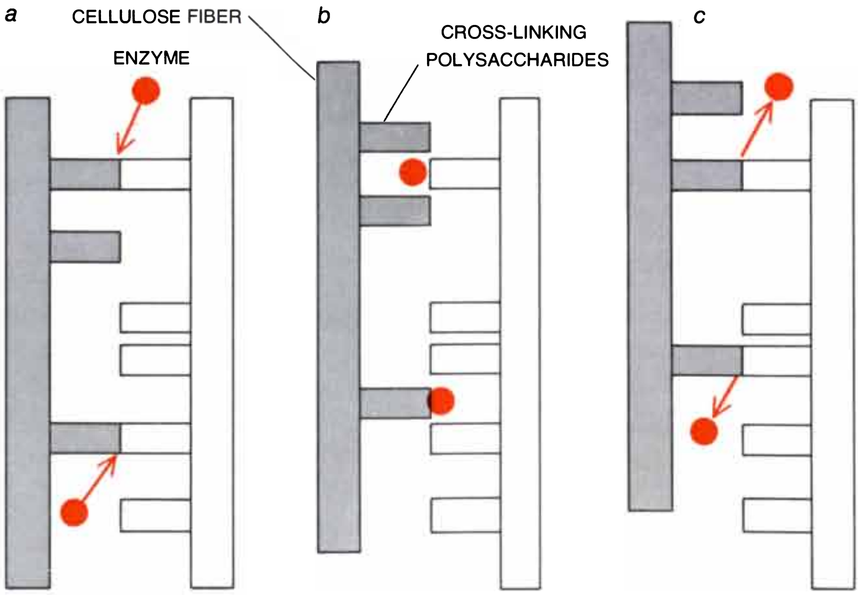
**STRIATIONS in the cell wall of a marine grass could be associated with fundamental structures. The wall is the gray region at right. Each of the striations, which are prominent only near the inner surface of the wall, may represent a cellulose fiber with its cross-linking polysaccharides. The electron micrograph was made by Mary E. Doohan and Newcomb.**



AUTORADIOGRAPH records the deposition of material in the cell wall during growth. The cells are from an oat seedling grown in a solution containing a sugar labeled with tritium, the radioactive isotope of hydrogen. After the cells had elongated, sections were placed on photographic film. The black dots are silver grains exposed by beta particles emitted by the tritium. Since the dots are widely distributed, material must be added to the wall throughout its length and thickness. Material deposited near the inner surface is incorporated into cellulose; elsewhere it enters the structure of the other polysaccharides.

functions are similar to those of xyloglucan, arabinogalactan and rhamnogalacturonan, even though their composition is different.

The strength and rigidity of the cell wall can readily be accounted for by the cross-linking of cellulose fibers, but the ability of the wall to elongate and its role in regulating growth have proved more difficult to explain. In the walls of cells that have not yet begun to elongate, the cellulose fibers are coiled around the diameter of the cell like barrel hoops. As the cell lengthens, the fibers straighten




EXTENSION OF THE CELL WALL might be regulated by an enzyme acting on bonds between the cross-linking polysaccharides. The enzyme would separate two molecules (*a*) and would become attached to one of them. The cellulose fibers could then shift in relation to one another (*b*) until the enzyme was able to join the polysaccharides to new partners (*c*). No enzyme capable of controlling such a process has yet been isolated from the cell wall, and it is not known which of the cross-linking polysaccharides the enzyme might act on.

out, and eventually they lie virtually parallel to the long axis of the cell. As the fibers shift and change their orientation they must slide past one another. Moreover, since neither the thickness of the wall nor its strength declines as the cell grows, new material must continually be added to the structure.

The new material might be added at one end of the cell, and in a few specialized tissues, such as root hairs and the germ tubes of pollen, that is apparently how the wall grows. In most growing cells, however, new material is added along the entire length of the cell. The process is conveniently studied by radioautography, in which precursors of polysaccharides are labeled with radioactive atoms and provided to the cell. After the cells have elongated they are placed on photographic film; the radiation emitted by the radioactive atoms exposes the film and thereby indicates where the labeled molecules have been incorporated in the cell wall. Radioautography was first employed in the study of the cell wall in 1959 by George A. Setterfield of Carleton University and Stanley T. Bayley of McMaster University; more recently Peter M. Ray of Stanford University has confirmed that new polysaccharide is synthesized in all parts of the wall. He supplied growing cells with sucrose that had been labeled with tritium, the radioactive isotope of hydrogen. Exposed areas of film were distributed uniformly throughout the wall [*see top illustration on opposite page*].

If the cellulose fibers in the walls of growing cells slide past one another, it is clear that covalent bonds in the cross-linking polysaccharides must be broken. At the same time the observation that the wall maintains its strength requires that new bonds be formed, both to reconnect molecules that have shifted their position and to secure new material added to the wall. The mechanism by which this realignment of bonds is accomplished is not known; we do not even know which of the three polysaccharides participate in the process. Perhaps the most effective way to investigate the structural changes necessary for elongation is by searching for an enzyme in the wall that mediates the transfer of bonds between polysaccharides. It might be identified by its ability to promote growth. The specificity of such an enzyme could reveal the position in the matrix of interconnected polysaccharides where the bonds break and shift and re-form. It could also be expected to illuminate the mechanism of growth regulation, at the least in dicotyledons and perhaps in all plants.

# GIANT CLAMS

## The tridacnids, related to cockles, include the largest bivalve in evolutionary history. Their size is probably due to the fact that photosynthetic algae live in their tissues and nourish them

by C. M. Yonge

As the tide retreats from the upper surface of the Great Barrier Reef of Australia a remarkable vista materializes. Visible for miles among the coral heads are the occasional rounded tops of the giant clam *Tridacna gigas.* The presence of these huge bivalve mollusks, which can be as much as four feet long, two feet wide and two feet high, immediately raises two biological questions. One is: How did such a large bivalve come into existence? The other has to do with the fact that the waters of tropical reefs are notoriously poor in mineral nutrients and therefore in the plankton that support the animal life of the sea. How, when an adequate food supply must be of vital importance to a bivalve as large as *T. gigas,* can it inhabit such an impoverished environment?

The answers to these questions are related. Long before any tridacnids existed the first modern corals made their appearance, and massive coral reefs arose in the world's shallow tropical seas. The reef-building corals presumably lived, as they do today, in symbiosis with unicellular brown algae: the zooxanthellae, photosynthetic organisms that have now been identified as a species of dinoflagellate, *Gymnodinium microadriaticum,* in a resting stage. Among all the many thousands of molluscan species this kind of symbiosis is found in only seven instances: in the six species of tridacnid clams and in one fairly close relative. This fact suggests not only that the tridacnids evolved in the same kind of coral-reef environment they inhabit today but also that their survival in these nutrient-poor waters depends in no small part on the nourishment provided by the photosynthetic algae they harbor.

To trace the evolution of the tridacnids it will be useful to review the anatomy of bivalves in general. One can, for example, better appreciate the bizarre upside-down position of the tridacnid shell when it is compared with the normal orientation of the shell among other bivalves. Within the phylum Mollusca the bivalves form the class Bivalvia, so called because of their two-part shell. While a bivalve is still in its larval stage it becomes enclosed within a fleshy mantle that secretes the shell. This outer covering consists of the two calcified "valves" and a connecting elastic ligament, and it can be tightly closed by the contraction of the animal's adductor muscles. When the muscles relax, the shell gapes slightly, giving the animal access to the surrounding water.

The mouth of a bivalve, however, is never in direct contact with the external environment. Both the oxygen and the nutrients the animal requires come to it through paired, enormously enlarged gills. The distinctive molluscan gills were named ctenidia by early anatomists because of their comblike structure; *ktenos* is the Greek for "comb." The organ has a remarkable morphological potential, and in the bivalves it has been modified into a living sieve that endows the animals with the most efficient means of ciliary feeding known in the animal kingdom.

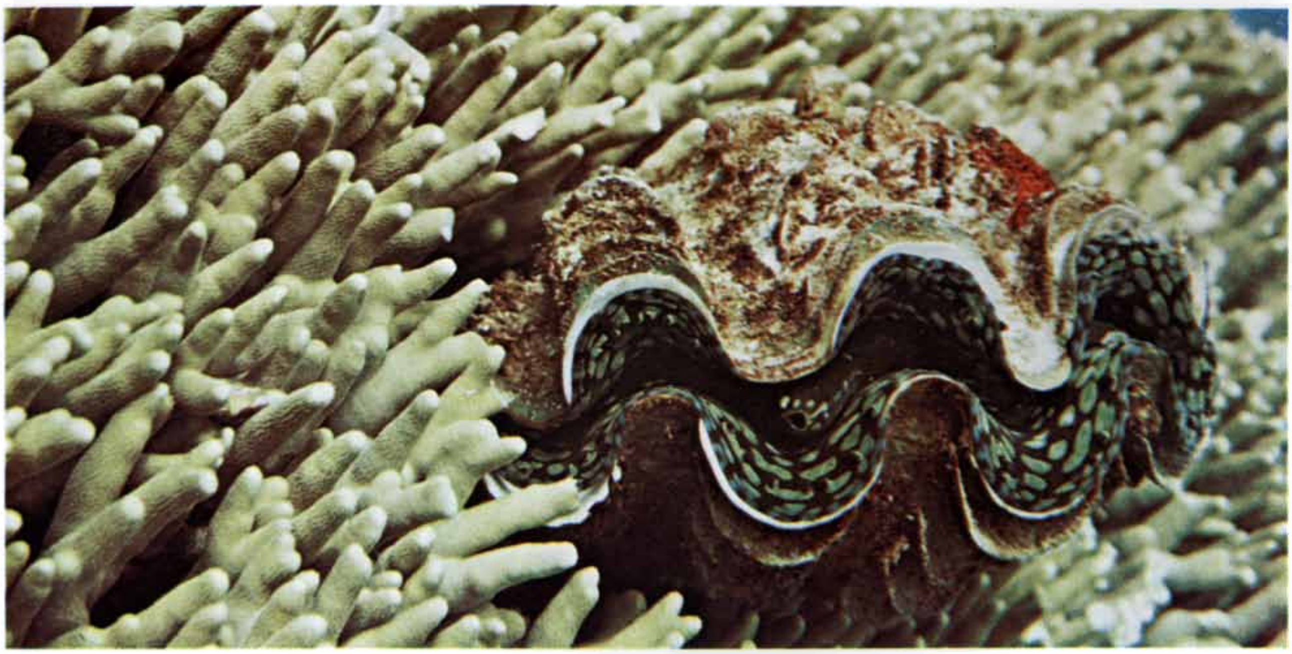
In its simplest form each of the paired gills of a bivalve consists of a main axis with lateral filaments on both sides that bear characteristic rows of cilia. Certain of the cilia create a powerful water current by their beating; others remove food particles and sediment from the passing water. The food particles, usually consisting of phytoplankton (plant plankton), are sorted, largely in terms of size, by ridged and ciliated palps before they enter the animal's mouth. At the same time other ciliated tracts accumulate the accompanying sediments for expulsion.

The bivalve's gills are enclosed in a respiratory cavity within the mantle. The water that passes through them enters the cavity through an inhalant opening and leaves through an exhalant one. Both openings are typically located at the posterior end of the animal. They are often modified into extensible and retractable siphons, and bivalves that are so equipped, such as the many kinds of burrowing clam, can penetrate deep into sand or mud. If the bivalve is a surface dweller such as a scallop or an oyster, its inhalant opening does not end in a narrow siphon but flares out. As the sole means of contact with the external environment the inhalant opening is fringed with receptive tentacles; in some bivalves, such as scallops and cockles, it is also surrounded by eyes.

The larvae of virtually all bivalves are free-swimming at first. Some adult bivalves remain mobile, others anchor themselves and others are anchored early in their life cycle and are mobile later. In all cases the same organ, the foot, plays a key role. An unattached bivalve such as a cockle uses its large, muscular foot to propel itself rapidly, sometimes with a leaping movement, to escape predators. In sedentary bivalves, such as mussels, special glands in the foot secrete an anchoring mass of fine threads known as the byssus, a term the Greeks applied to a closely woven cloth.

These are the generalizations concerning bivalves that are pertinent here. As a major class of mollusks the animals have exploited their potential with striking success. That is true not only in terms of the size of many bivalve populations but also in terms of the diversity of the bivalve form. Although the morphological theme is basically simple, the variations played on it have brought forth a large array of bivalve superfamilies, each exhibiting a particular struc-

**SUNLIT GIANT CLAM** is examined by a diver in the waters off the Eniwetok atoll in the Marshall Islands. This specimen is the species *Tridacna gigas*, largest of giant clams. Some specimens of *T. gigas* have exceeded four feet in length and 550 pounds in weight.



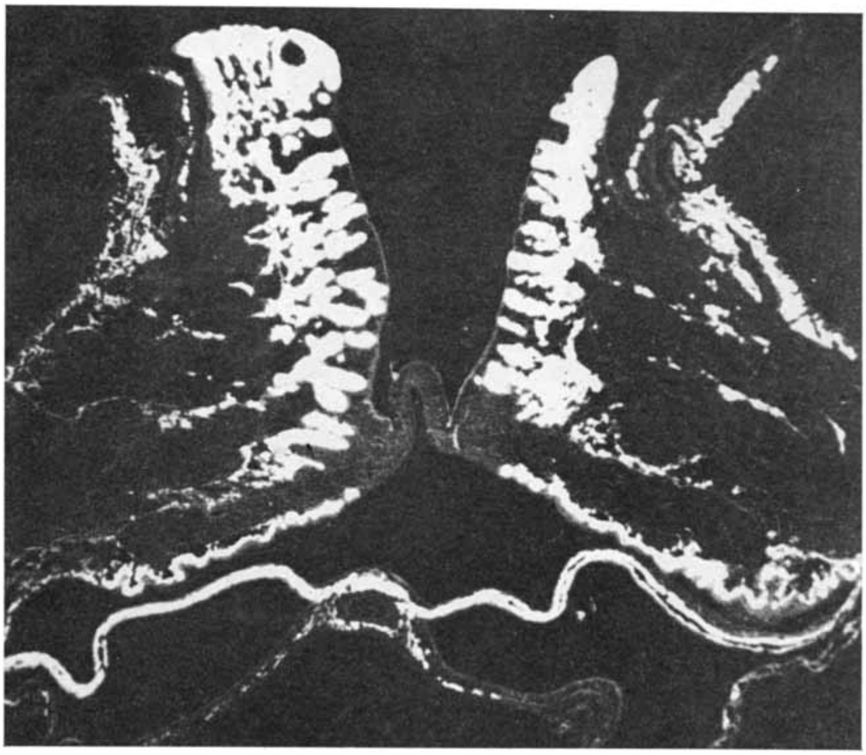
MIDDLE-SIZED GIANT, *Tridacna squamosa*, does not exceed 16 inches in length. Early in life it is attached to the reef by its byssal threads. As it grows larger its weight also helps to hold it in place. Its mantle tissue, which shows a spotted pattern in this specimen photographed at Eniwetok atoll, receives the sunlight that penetrates the water. In this tissue live most of the symbiotic algae.

MANTLE PATTERN of fine light stripes is displayed by another tridacnid, photographed in the waters of Malakal Harbor at Koror in the Palau Islands. This is an unanchored species, *Hippopus hippopus;* its mantle does not extend beyond the margins of its shell.

tural pattern. Moreover, within each pattern adaptation and specialization can run riot.

The Cardiacea, the superfamily that includes the tridacnids, provide an excellent example. In addition to the more specialized tridacnids this superfamily includes the cardids, or cockles, which number some 10 genera and a great many species. Beaches and shallow zones of sand and sandy mud the world over are the habitat of the cosmopolitan cockle, and the populations of some species reach astronomical numbers. More than one adaptive trend evident in the highly successful cockle family is suggestive of the pattern of tridacnid evolution. To understand the one family some knowledge of the other is needed.

One cockle trend is a tendency toward enlargement. The giant cockle of East African waters can be as large as a coconut; a New World cockle, *Cardium elatum,* which is common in the Gulf of California, is equally impressive. A second significant cockle trend is apparent in the typically globular shape of its conspicuously ribbed shell. The rotundity of the shell prevents the cockle from burrowing very far. At the same time the ribbing of the shell increases the stability of the animal within the surface layers of the sand it inhabits.



**TRANSVERSE SECTION through the siphonal tissues of *Tridacna maxima* is seen in a radioautograph. The clam was exposed for an hour to carbon dioxide labeled with radioactive carbon atoms. Symbiotic algae, clustered in the siphonal tissues that are exposed to sunlight, incorporated the carbon dioxide in the course of photosynthesis. Radioactive carbon makes algae appear as bright areas. Radioautograph was made by Thomas F. Goreau.**

A third trend is apparent in the heart cockle, *Corculum cardissa,* of the tropical Pacific. The very thin shell of this cockle has been greatly compressed, not laterally but from end to end [*see illustration on next page*]. The animal works into the bottom with its anterior half undermost, so that its posterior half, with short siphons extended, remains exposed. The tropical sunlight that illuminates the shallows penetrates the translucent shell. Apart from the tridacnids the heart cockle is the only bivalve that harbors algae; these photosynthetic symbionts are found in the gills and other tissues of the animal that are exposed to the light.

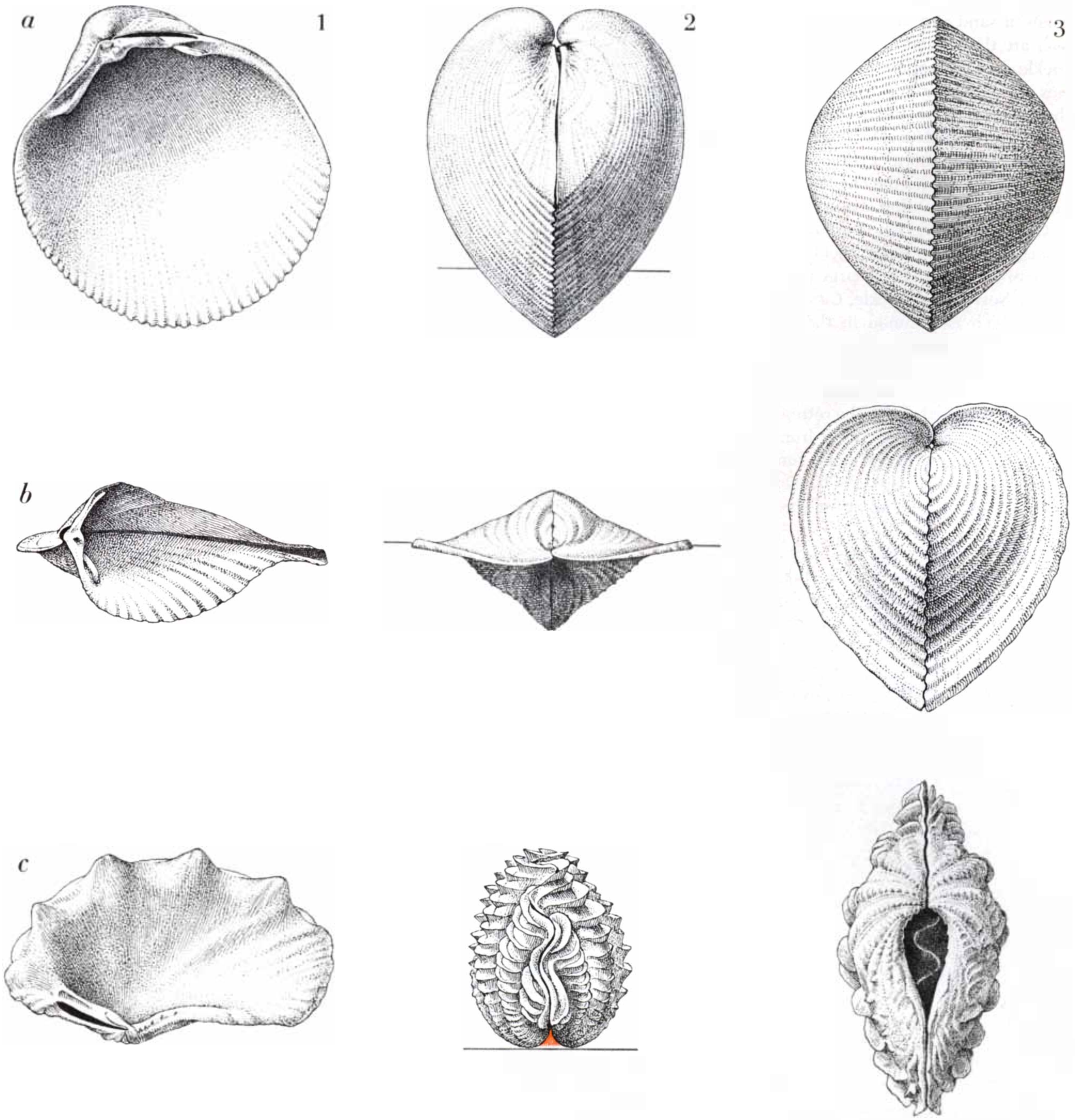
The tridacnids also vary substantially in size and shape. Five of the six species in the family are in the genus *Tridacna;* the other is in the genus *Hippopus.* All are confined to the tropical waters of the Red Sea, the Indian Ocean and the western Pacific. *Tridacna crocea,* which can reach a length of six inches, is the smallest species and is also unique in habitat. Other tridacnids may grind shallow pockets into the limy rock where they take up residence, but *T. crocea,* by repeated contractions of its byssal muscles, bores so deep into the rock that the margins of its shell valves are all that remain visible [*see bottom illustration on page 103*]. The species is found from the Nicobar Islands of the Indian Ocean eastward to Fiji in the Pacific.

Three tridacnid species are, relatively speaking, middle-sized. The length of *Tridacna maxima* does not exceed 14 inches; the upper limit for *Tridacna squamosa* and *Hippopus hippopus* is 16 inches. *T. maxima* is found from the Red Sea to Pitcairn Island; *T. squamosa,* from the Red Sea to Tonga. Both, like *T. crocea,* spend their life attached to the reef rock, often partly covered by growths of coral. *Hippopus,* however, remains attached only from the end of its larval stage until it has grown to about the size of a clenched fist. Its byssus threads then atrophy, and the currents that pile up sand in the lee of the reef roll the detached clam to the same shelter. The distribution of weight in *Hippopus* is such that the animal comes to rest in an upright position, and its siphonal tissues, extending up to the margins of the widely opened shell, catch the sun. *Hippopus* is found from the Nicobar Islands to Tonga.

*Tridacna derasa* is the next to largest in the family; its shell can be more than 20 inches long. Like *T. crocea* (and *T. gigas*) it is found between the Nicobars and Fiji; like *Hippopus* (and *T. gigas*) it loses its byssal apparatus as its size increases and ends up as an unattached animal.

The term *Tridacna* is from the Greek *tridaknos,* "eaten at three bites"; this was a learned joke of the 18th-century naturalist Jean-Guillaume Bruguières, who named the genus. Although bivalves that range from six to 20 inches in shell length can scarcely be called small, the smaller five species are dwarfed by *T. gigas.* Even discounting the more fantastic stories about this species, the attested data are quite impressive enough. One specimen, collected in the Philippines early in this century and now on display at the American Museum of Natural History, weighs 579.5 pounds. The two empty valves of another *gigas,* four feet six inches long, weigh 507 pounds. In the 16th century the Republic of Venice sent a pair of *gigas* valves, three feet four inches long, to François I of France as a curiosity. They can still be seen in use as fonts for holy water at the church of St. Sulpice in Paris.

The habitat of the tridacnids, the upper surface or sandy lee of coral reefs, is covered by at most a few fathoms of exceptionally clear water. Thus the tissues that harbor the clams' symbiotic algae are exposed to intense tropical sunlight. Only when the animals are uncovered by the tides or are stimulated by the shadow of a predator do they withdraw their exposed tissue and close their shell valves. The sunlight is of course essential to the photosynthetic activity of the algae, but it is potentially lethal to the clam. The hazard of exposure to harmful wavelengths has been overcome by the evolution of a protective pigmentation. The pigments in the exposed tissue are contained in fixed cells known as iridophores. Mainly in the color range of blue to green or brown to yellow, they give rise to an almost infinite variety of patterns that are at their most vivid among the smaller species. The exposed tissues of *T. crocea* are invariably blue; those of *Hippopus* and *T. gigas* are usually olive green.



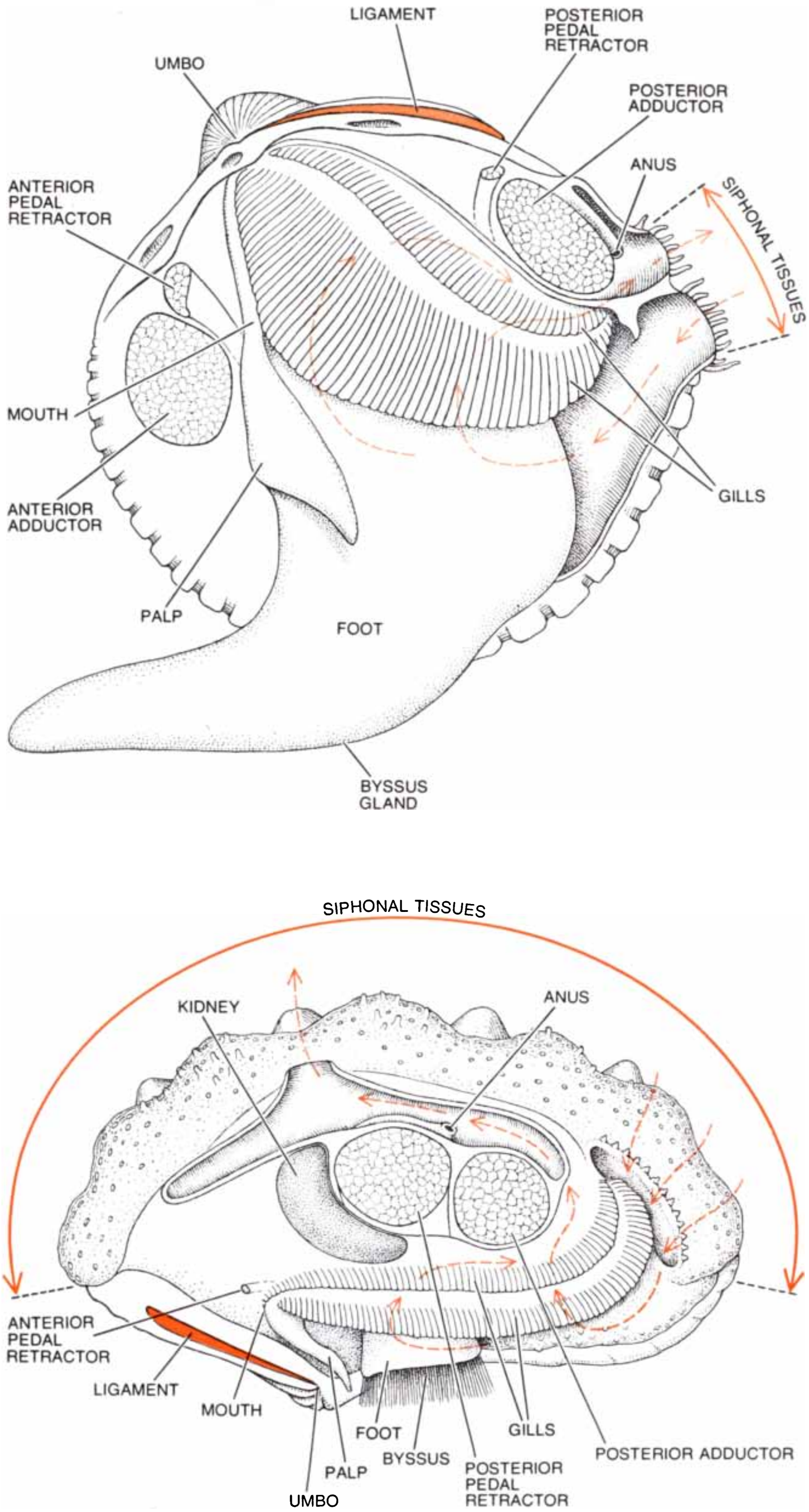

**SHELLS OF THREE BIVALVES** of the superfamily Cardiacea are shown in three views: (1) the inside of the right valve oriented as in life, (2) both valves together, rotated 90 degrees around the vertical axis from the first position, and (3) both turned 90 degrees around the horizontal axis from the second position, showing the shell from below as it lies in life. The lines suggest each animal's position in or on the sea floor. The first shell (*a*) is that of a giant American cockle, *Cardium elatum;* it is six inches long. The next (*b*), the heart cockle, *Corculum cardissa,* is 1.5 inches long. The last (*c*), *Tridacna maxima,* is five inches long; a mass of threads (*color*) emerging from its shell is the byssus that anchors the animal to the reef. The anchoring threads are secreted by glands in the foot of the clam. The muscular foot of the cockle also emerges on the underside, which is opposite hinge in this bivalve.

In a typical bivalve at rest the foot of the animal projects between the free margins of the shell valves; the margins are on the underside, the shell hinge being uppermost. If a tridacnid is to provide its algal partners with sunlight, however, it must rest in such a way that its exposed tissues face the sun. In all tridacnids the foot (together with the attaching byssus, when it is present) remains on the underside of the animal, but the margins of the shell valves, with their brilliantly colored tissues, are exposed at the top. The animals have achieved this paradoxical result in the course of their evolution by twisting themselves, so to speak, so that the hinge of the shell has moved from the top around to the underside, ending up next to the opening through which the byssal threads emerge [*see illustration at right*].

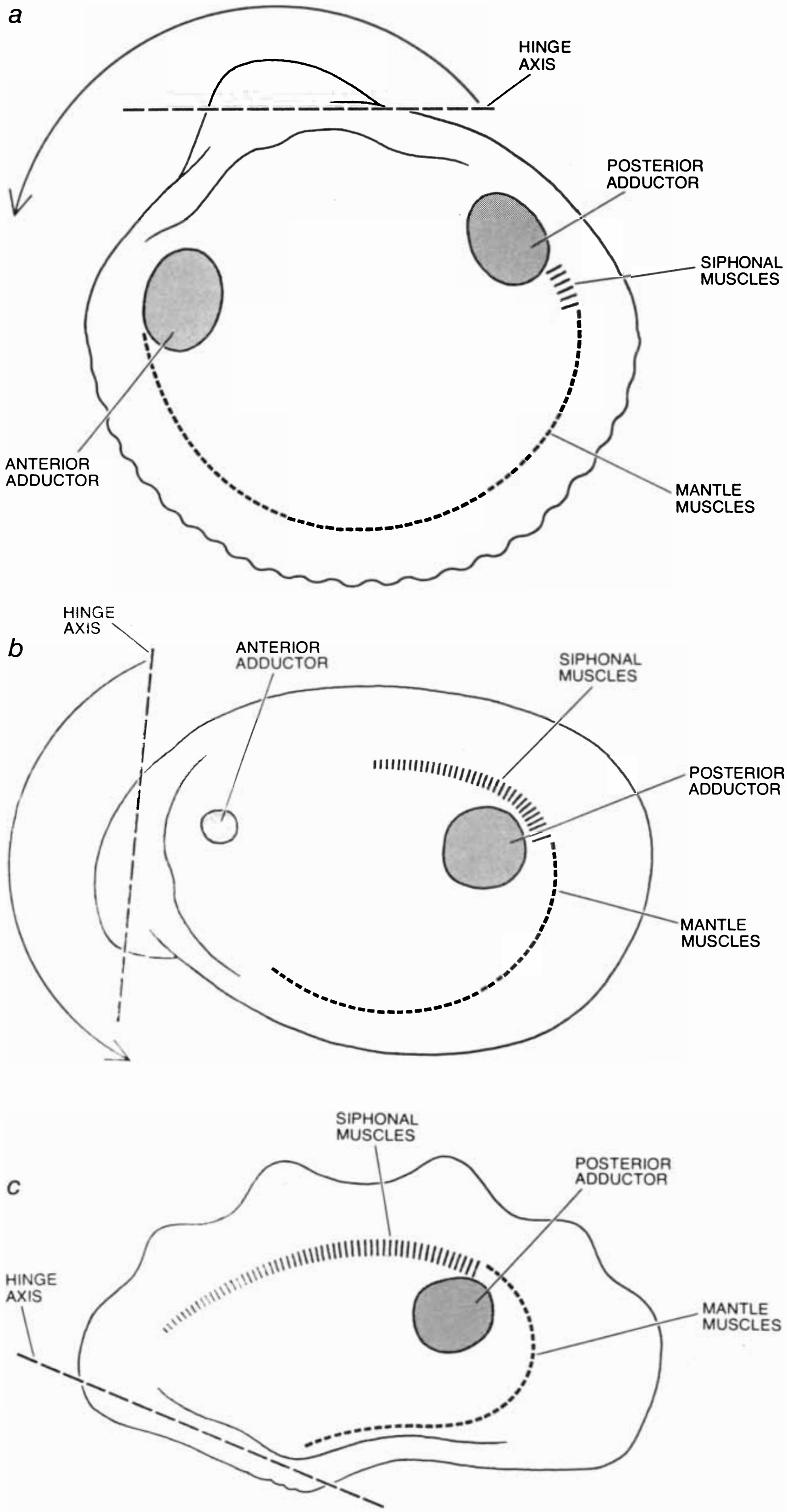
This process of rotation was the consequence of an extensive enlargement of the tissues that house the algal partners of the clam. It can most easily be visualized if one compares a cockle and a tridacnid, both animals being oriented in the basic foot-down attitude. The shell of the cockle is thus in the normal bivalve position, with its hinge uppermost. Imagine now that the cockle's shell is slowly rotated in relation to its enclosed body, while the body remains fixed by the foot. The rotation not only eventually brings the hinge around to the underside, next to the foot, but also stretches the soft tissue in the region between the inhalant lower siphon and the exhalant upper one [*see illustration on next page*].

The rotation, a process that probably required millions of years, may have been achieved by slow and gradual stages or by a few major mutations. The end result, however, was the same: an ancestral cockle had been transformed into a tridacnid. The siphonal tissues were now extended along the length of the upper surface, ready to cover the opening between the margins of the shell valves, and the shell hinge was now adjacent to the foot. The rotation had the further effect of squeezing out one of the ancestral cockle's two adductor muscles, so that, like scallops and oysters, although for entirely different reasons, tridacnids are single-muscle bivalves.

Rotation, in short, is the anatomical highlight of tridacnid evolution. To understand why the animal evolved at all, however, one must put the anatomical event in historical perspective. The cockles, the obvious ancestors of the tri-




**UPSIDE-DOWN ANATOMY of a tridacnid (*bottom*) is compared with the anatomy of a cockle (*top*); both bivalves are shown in a foot-down position. This orientation places the cockle's shell-hinge ligament (*color*) uppermost. The cockle's paired siphons are at right; broken arrows indicate inward and outward flow of water. The cockle's foot is extended beyond the gape of its shell. The byssal threads secreted by the foot of the tridacnid also extend beyond the shell, passing through the opening near the shell hinge. A great enlargement of the tridacnid's siphonal tissues (*colored arrow*) has been responsible for moving the shell hinge to the underside. A reconstruction of the process appears on the next page.**




**POSSIBLE SEQUENCE in the evolution of the tridacnids is illustrated here in terms of a rotation of the shell. The process begins (*a*) with an ancestral cockle, shell hinge uppermost; rotation of the hinge axis is counterclockwise. With rotation half complete (*b*) on this hypothesis, stretching has extended the siphonal muscles of the tridacnid-to-be and may have reduced the anterior adductor muscle. Continuing rotation (*c*) carries the shell hinge to its ultimate position next to the foot. Enlargement of the siphonal muscles progresses, the anterior adductor is lost and what emerges is the basic tridacnid-family morphology.**

dacnids, originated in the same period of the Mesozoic era that witnessed the rise of the modern corals; this period was the Triassic, which began some 225 million years ago. In the succeeding period, the Jurassic, the corals proliferated with remarkable success. It is believed it was at this time that modern corals first became separated into those that build reefs and those that do not. The corals that built reefs, living in symbiotic association with photosynthetic algae, were confined to the shallows of tropical seas; the corals that did not build reefs, living without symbionts, became widely distributed in all latitudes and down to great depths.

We may visualize the sandy shallows in the lee of these Mesozoic reefs as being the habitat of the cockles that were eventually to evolve into tridacnids. The heart cockle, the only other bivalve that is symbiotic with algae, evolved even more recently than the tridacnids, and so it can tell us nothing about the emergence of the tridacnids. Its existence nonetheless demonstrates that suitably illuminated surface-dwelling cockles can become the hosts of algae that are already prepared for life in the tissues of some host animal.

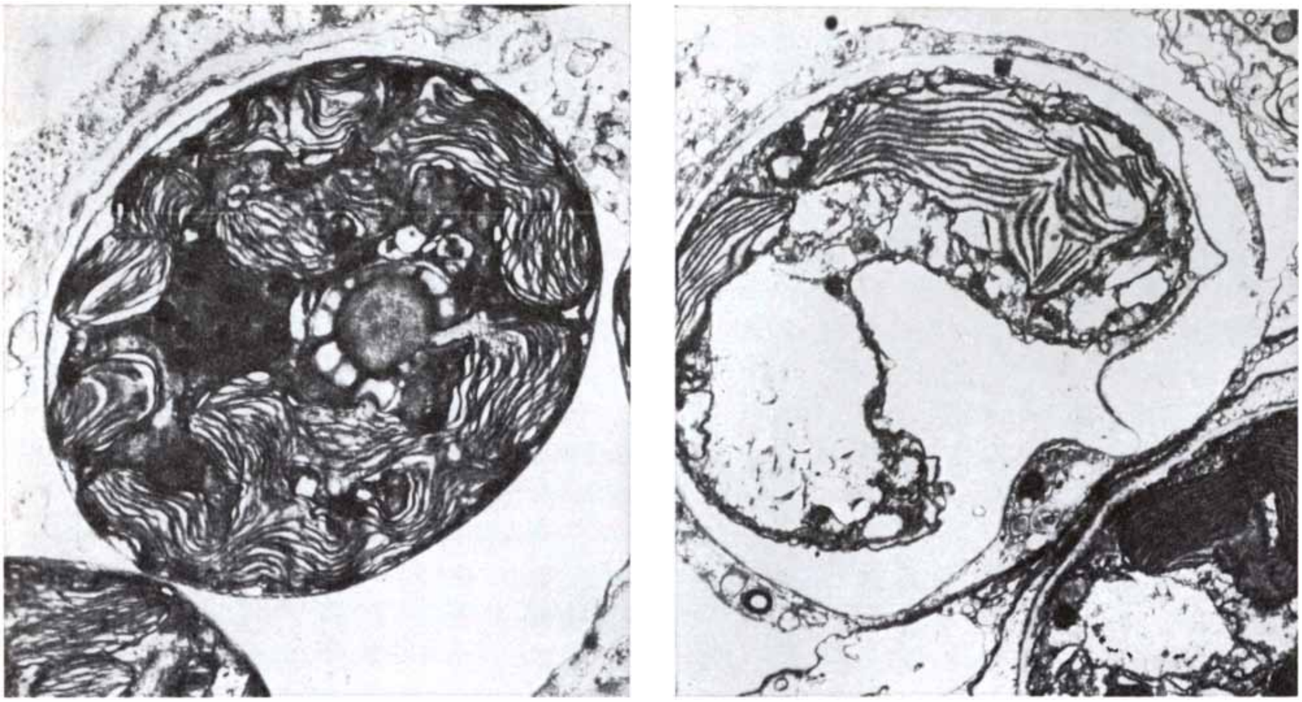
But how did the host-guest relation develop? The reefs that sheltered the evolving cockles, of course, harbored vast populations of algae living symbiotically in the corals. The relationship between the algae and the corals, however, can best be considered a kind of infection: an invasion by the plant cells that is certainly to their benefit. Corals are exclusively carnivorous animals; they will not accept plant food and so offer no threat to the algae. At the same time their metabolic processes provide the algae with elements such as phosphorus and nitrogen, which are essential for protein synthesis and yet are available only in trace amounts in the mineral-poor reef waters.

How the corals benefit from the association is less apparent. The algae multiply and eventually degenerate, but there is no evidence that the corals digest them. Some organic material does pass from the plant cells into the corals' tissues. The exact significance of the transfer remains uncertain, although it is clear that the algae assist in the process of coral calcification. In the final analysis, however, the algae are the organisms that gain the initial advantage from the association, and the "initiative" must therefore be attributed to them.

Was the first infection of the ancestral cockle by algae equally equivocal and

LARGEST GIANT, *Tridacna gigas,* is not anchored to the reef by byssal threads, but its weight keeps it in place. The clams are often partly concealed by growths of coral. This specimen was photographed at low tide on top of the Great Barrier Reef of Australia.

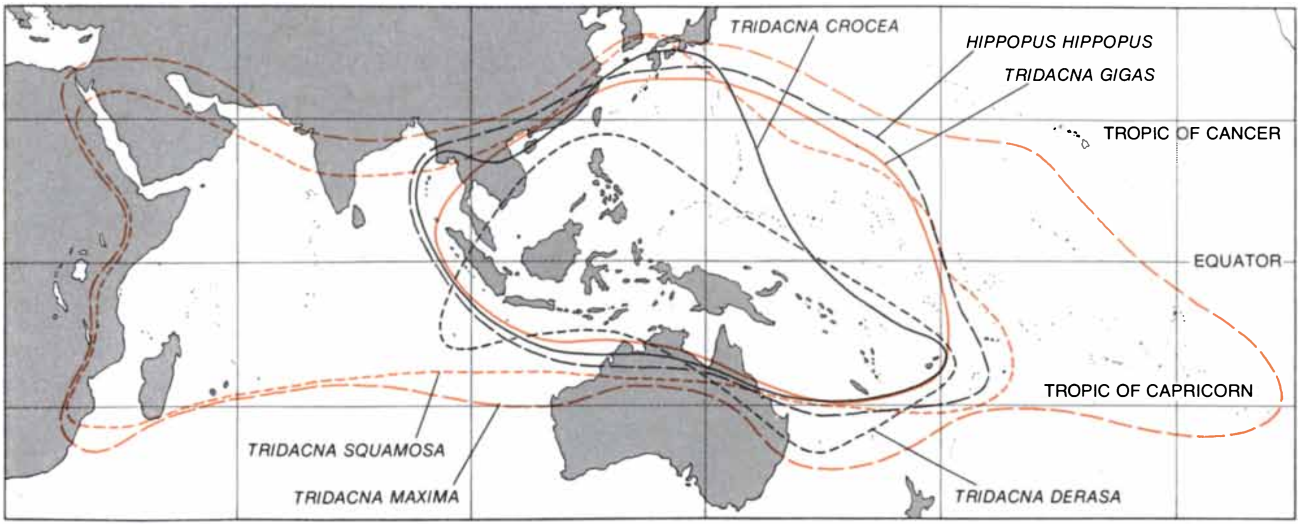
SMALLEST GIANT, *Tridacna crocea,* bores its way into the reef rock, grinding its shell inward by repeated contractions of the byssal muscles until only the edges of the shell are visible. This photograph made by author shows several *T. crocea* at low tide.



**YOUNG AND OLD ALGAE come from the siphonal tissue (*left*) and the gut (*right*) of tridacnids from Micronesia. The dark area in the young specimen is the nucleus; the closely packed strands are the lamellae of the photosynthetic chloroplasts. In the aging alga the lamellae have spread apart and the nucleus is no longer visible; the symbiont is being digested by a scavenger blood cell. These electron micrographs were made by Peter V. Fankboner of Simon Fraser University; algae are magnified 10,000 diameters.**

seemingly one-sided? We have no way of being certain, but to judge from modern tridacnids two conclusions seem tenable. First, the invading algae must already have been fully adapted for life within animal tissues. They could scarcely have been free-living forms, because the bivalves, supremely equipped for the collection and digestion of just such plants, would have promptly consumed them. Moreover, the algae do not invade all the tissues of a bivalve but are confined to those that are normally illuminated during the daylight hours.

These tissues are in the siphonal region, and as we have seen they have become greatly enlarged, in both length and width, in the course of tridacnid evolution. Thus they have offered the algae increasingly roomy accommodations. It is this fact of siphonal enlargement that leads to the second conclusion. Once algae became established in the sunlit part of the clam some advantage must have accrued to the host animal. Why else would the tissues have been stretched forward and extended laterally in a progressive series of changes occupying millions of years? The siphonal region has become so large that when one looks down through the clear reef water at an undisturbed tridacnid today, these strikingly pigmented tissues




**DISTRIBUTION OF TRIDACNIDS is shown on this map. Most widespread are *Tridacna maxima*, found from the Red Sea to Pitcairn Island, and *T. squamosa*. The most restricted are *T. gigas* and *T. crocea*. *Hippopus* and *T. derasa* are intermediate in distribution.**

completely obscure the two great shells under them.

From study of the tissues the algae inhabit it is evident that the advantage accruing to the clam from the presence of its symbiotic partners is nutritional. The inhalant and exhalant siphons of the tridacnids are backward extensions of the mantle, the tissue that enfolds the body, adds new shell and thickens old shell as the animal grows. In the tridacnids, as in all other bivalves, the margin of the mantle has three parallel folds. The outermost fold is the one that secretes shell. The middle fold gives rise to sensory tentacles and in some instances eyes. The muscular inner fold controls the flow of water.

The inner fold is also the one that has become enormously extended. Here, apparently housed in the individual blood cells that occupy the blood spaces of the thickened tissue, the algal partners of the tridacnids congregate, multiplying most vigorously in the parts of the tissue that are best illuminated.

In other bivalves the blood cells often act as phagocytes, scavenging and digesting pathogens and other foreign matter. In tridacnids it has been observed that the tubules of the digestive gland are surrounded by blood spaces filled with cells that contain degenerating and apparently semidigested algae. These algae, however, never enter the gut. When this writer first studied these animals, he interpreted the condition of the degenerating algae as proof of a process whereby surplus symbionts were conveyed from the illuminated areas where they multiply into deeper tissues, there to be digested in the blood cells for the nutritional benefit of the clam. (The residue after digestion would have been voided by way of the animal's enlarged kidneys.)

What stimulates the transport of the algae from sunlight to shadow was a mystery then and remains a mystery now. Recent studies with the electron microscope suggest, however, that what seemed to be semidigested algae may actually be senile algae. Perhaps that condition provides the stimulus for the transport. In any event tridacnids may not get as much nutriment in this way as was once considered probable.

What remains certain is that the photosynthetic algae release substantial quantities of organic matter into the clam's bloodstream. The principal product is a carbohydrate, glycerol. The release is readily demonstrated by exposing the clam to carbon dioxide labeled with radioactive carbon atoms. The algae in the mantle at once take up the carbon dioxide as a part of their photosynthetic activity. Almost immediately afterward, as radioautographs show, the labeled carbon is found in the glands of the foot where the byssus threads are secreted, in the pair of large mucus glands in the mantle cavity, in gill areas associated with food transport and, most interesting of all, in certain cells within the style sac. The style, a uniquely molluscan structure, plays an essential role in the digestive processes of these animals by liberating enzymes and mixing food in the stomach.

The evidence from radioautographs shows not only that certain carbohydrates produced by algal photosynthesis are available to the host animal but also that the carbohydrates are rapidly incorporated into the metabolic processes of the host. The tridacnids, however, also need a supply of protein. This supply they obtain in part by ingesting all the plant plankton that is available. Their dependence on this normal source of bivalve nutrition is evident in their retention of the structures that all bivalves use for the purpose: feeding gills, selective palps and an elaborate digestive system.

As we have seen, however, the tropical seas in which the tridacnids live are notably poor in the mineral nutrients that support abundant planktonic life. As a result the proportion of the tridacnids' protein budget that comes from the uptake of plankton must necessarily be meager. Nonetheless, all six species in the family are large compared with the average bivalve, and *T. gigas* is not only the largest living bivalve but also the largest bivalve known to have evolved in the past 600 million years. (Some Mesozoic bivalves of the rudist group may have had larger shells, but the animal within was much smaller.) Moreover, there must be an upper limit to the size of any animal that feeds only by ciliary action, and that limit appears to have been far exceeded by *T. gigas*.

When the accumulated evidence is weighed, it is hard to escape the conclusion that the tridacnids get a significant part of their protein by digesting their surplus algal guests, whether or not the digested algae have become senile and degenerate along the way. Whatever uncertainty there is about the "how" of the process, it appears to be beyond question that the algae for whose environment and exposure to light the bodies of the tridacnids have become so strikingly adapted pay rent to their hosts by providing as nourishment both their photosynthetic products and themselves.


# THE ROTATION OF THE SUN

## The sun turns once every 27 days, but some parts turn faster than others. Such variations are clues to interrelated phenomena from the dense core outward to the solar wind that envelops the earth

by Robert Howard

When Galileo turned his telescope on the sun in 1610, he discovered that there were dark spots on the solar disk. Observing the motion of the spots across the disk, he deduced that the sun rotated once in about 27 days. One of his contemporaries, Christoph Scheiner, undertook a systematic program of observing the spots. From these observations Scheiner found that the rotation period of the spots at higher solar latitudes was slightly longer than that of the spots at lower latitudes. In the middle of the 19th century R. C. Carrington, a wealthy English brewer and amateur astronomer, determined with good precision the amount of the variation of the sun's rotation rate with latitude.

Scheiner's observations suggested that the sun does not rotate as a simple solid body. Since we now know that the sun is a gas throughout, it does not surprise us that it does not rotate as a solid. One might have expected, however, that the spots closer to the sun's equator would move slower than the spots at the higher latitudes, just as the outer planets of the solar system move slower in their orbits than the inner ones. The fact that the equatorial regions rotate faster than the rest of the sun implies that an excess of angular momentum—the momentum of the sun's rotation—must be transferred from the higher solar latitudes to the equatorial regions. This fact and its implications yield information about the structure of the sun's interior and the nature of its activity.

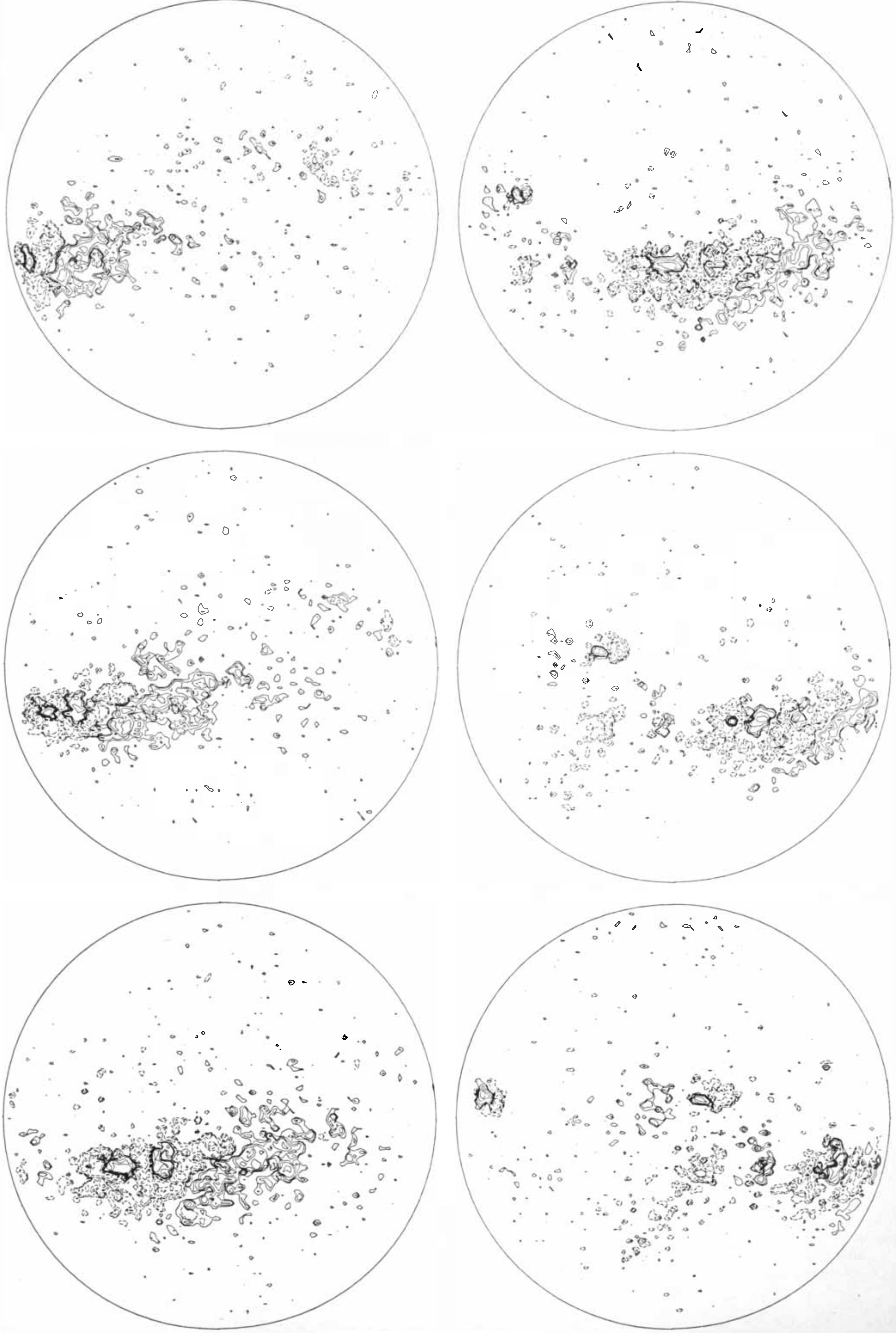
There are two basic methods for precisely determining the rotation of the sun at a particular latitude. The first is to time the passage of some tracer (such as a sunspot) across the solar disk. The second is to photograph the spectrum of the sun; the spectral lines of the solar atmosphere will be Doppler-shifted because the gas that gives rise to them is moving, and the amount of the shift is proportional to the velocity of the gas in the line of sight. Unfortunately for solar observers each method has disadvantages that limit its usefulness.

Timing a tracer as it crosses the disk of the sun is a good technique for determining the solar rotation rate only if the tracer meets certain requirements. First, it must survive long enough unchanged in its appearance to be useful over some reasonable period of time. Second, it must have a clearly defined structure, so that its position can be accurately determined. Third, it must be at the same altitude in the sun's atmosphere when it is seen at the center of the solar disk and when it is seen at the edge. Last, it must not wander around the solar disk in some systematic way not directly related to the sun's rotation.

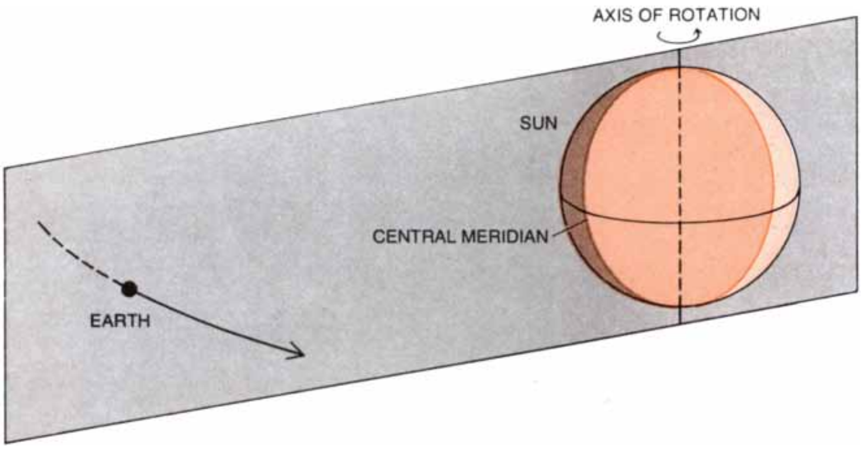
Although no features on the sun meet all these requirements, sunspots are still the easiest to observe, and they have been studied more than any other tracer. Thus they have probably provided the most accurate determinations of the sun's rotation. When sunspots are observed with a small telescope, they appear simply as spots on the photosphere: the bright surface of the sun that is seen in ordinary white-light photographs. In larger telescopes they may appear as saucer-shaped depressions near the edge of the sun. Therefore it is hard to be sure that the same point in the sunspot is being used for the purpose of measurement as the spot traverses the solar disk and is seen from a different angle each day. In order to avoid the problem, students of the sun's rotation prefer to use long-lived spots that cross the central meridian of the sun more than once. The central meridian is defined as the intersection of the sun's visible surface with the plane that passes through the sun's axis of rotation and the earth; when a sunspot crosses the central meridian, the effect of its three-dimensional form is minimized and its position can be most precisely measured.

Only a small fraction of sunspots live long enough to cross the central meridian more than once. The spots with the longest lifetime are the ones found on the leading edge of groups of sunspots,

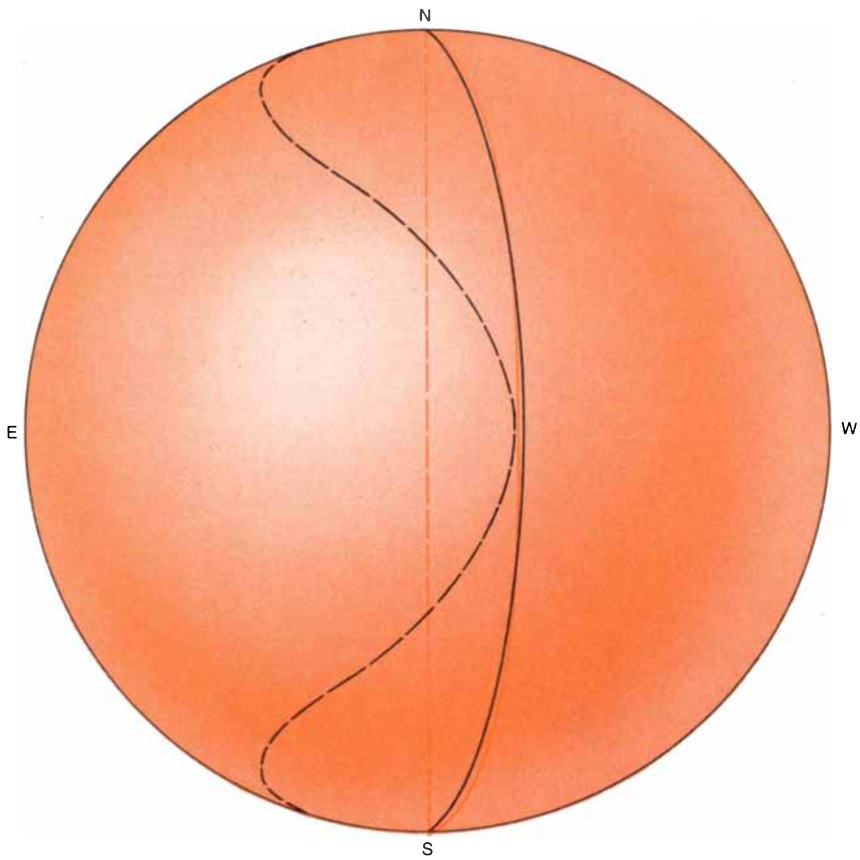
**SUN'S ROTATION** can be monitored by noting the daily progress across the solar disk of a tracer such as a sunspot or a gaseous filament. Such features are associated with magnetic fields, which can be detected directly by means of a solar magnetograph. The six magnetograms on the opposite page were made with the 150-foot tower telescope at the Mount Wilson Observatory. The sequence reads from top to bottom and shows the magnetic activity on the sun at intervals of every other day from May 30, 1974, through June 9, 1974. The contours on the magnetograms represent equal-strength areas in the magnetic fields. The strength in gauss of the fields at successive contour intervals is five, 10, 20, 40 and 80. (The strength of the earth's magnetic field is less than one gauss.) The solid contours represent positive magnetic fields; the broken contours represent negative fields. The lifetimes of the smallest magnetic features are less than a day, so that in general it is possible to trace the daily rotational movement of only the larger magnetic features. Strongest of active regions that are seen here are associated with sunspots; it is difficult to determine the exact location of spots, however, because angular resolution of magnetograms is low. Evolutionary changes within active regions somewhat alter their appearance from day to day.



and so these are the ones that are most commonly monitored. That is actually unfortunate, because the preceding and following members of a sunspot group tend to separate early in the lifetime of the group. In addition the preceding spots tend to exhibit systematic motions of their own later in their lifetime. A further disadvantage of using sunspots as rotation tracers is that they are rarely seen above a solar latitude of 35 degrees. Thus they can be used only for determining the rotation of the sun at rather low latitudes.




**CENTRAL MERIDIAN OF THE SUN** as it is seen from the earth is defined as the intersection of the portion of the sun visible from the earth (*color*) with the plane (*gray*) defined by the sun's axis of rotation and the earth. Longitudinal positions of the various markers that are monitored to study sun's rotation are referred to sun's central meridian.

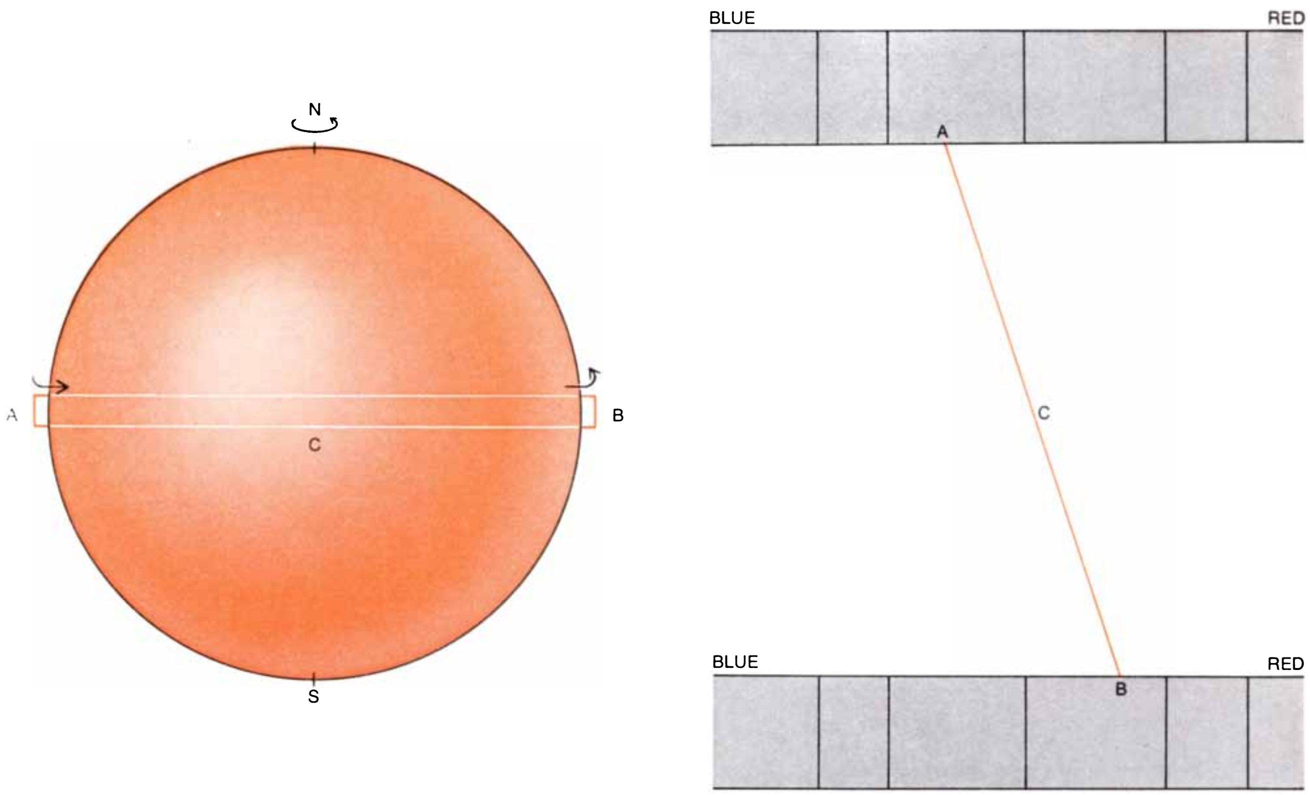



**SUN DOES NOT ROTATE AS A SOLID BODY** but rotates differentially with latitude. The lines in color indicate position of tracers after one day (*solid line*) and 27 days (*broken line*) if the sun rotated as a solid body. The lines in black indicate their actual positions after one day (*solid line*) and 27 days (*broken line*) and illustrate the effects of the sun's differential rotation. In general the higher the latitude, the longer the rotation period.

A second kind of tracer is the long filaments of gas in or above the solar chromosphere. The chromosphere is the transitional layer between the photosphere, which has a temperature of 6,000 degrees Kelvin, and the solar corona, which paradoxically is much hotter: about two million degrees K. The chromosphere can be observed only at the wavelengths of certain spectral lines, notably the line designated hydrogen alpha in the red region of the spectrum. Photographs of the chromosphere made in the light of the hydrogen-alpha line show an abundance of lovely detail. Although most of these features are too short-lived or too ill-defined to be used for accurately determining the rotation rate of the chromosphere at various latitudes, large dark filaments are fairly reliable tracers. The filaments are actually clouds above the chromosphere that appear dark when they are seen projected against its bright surface but appear bright when they are seen extending beyond the edge of the solar disk. They are not ideal tracers because their appearance changes too rapidly. Their lifetime is not negligible, however, and they are present at higher solar latitudes than sunspots. For these reasons their rotation characteristics have been studied in detail.

If the photosphere and the chromosphere show rotation, what about the solar corona? This question is not easy to answer. The corona is so faint compared with the rest of the sun that it can be viewed only during a total eclipse of the sun or with the aid of the coronagraph: a telescope equipped with an occulting disk that blocks the light of the photosphere as the moon does (although not as effectively). In either case the exact connection between features of the solar disk and features of the corona is hard to determine. Moreover, the coronal features are so poorly defined that it is difficult to measure their size and position. The rotation of the corona may therefore be measured accurately only by correlating observations that extend over at least several months.

Richard Hansen, S. F. Hansen and Harold G. Loomis have measured the rotation period of the corona with a specially designed instrument attached to a coronagraph on the mountain Haleakala on the Hawaiian island of Maui, and they have found that the period varies somewhat from year to year. E. Antonucci and Leif Svalgaard of Stanford University have found that the rotation rate of the corona varies with the age of coronal features. The long-lived features




**LINES IN SUN'S SPECTRUM ARE SHIFTED** from their normal position because of the Doppler effect if there is a relative motion along the line of sight between the source of the lines and the observer. Since the sun rotates from east to west (*left*) the eastern limb of the sun (*A*) is approaching observers on the earth and the western limb (*B*) is receding. Thus spectral lines emitted by gas (*right*) on the eastern limb are shifted toward the blue region of the spectrum (*A*) and the lines emitted by gas on the western limb are shifted toward the red end (*B*). If the slit of the spectroscope is projected across the sun's equator, the lines on the spectrogram will be tilted. (In illustration the magnitude of tilt is exaggerated.) Spectral line from gas on central meridian (*C*) will not be shifted.

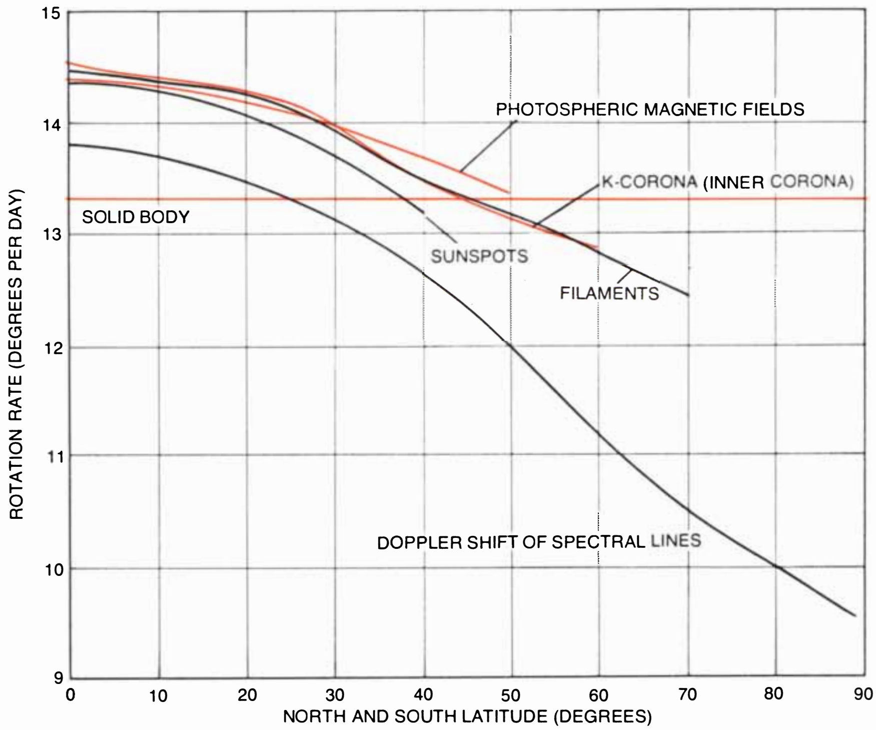
rotate almost as though they were part of a rigid body, whereas the short-lived features rotate much as the sunspots do.

In 1908 George Ellery Hale of the Mount Wilson Observatory found that sunspots are associated with strong magnetic fields. Only within the past two decades, however, has it been possible to reliably measure the weaker magnetic fields that extend over large areas of the solar surface outside the sunspots. Some years ago Václav Bumba of the Ondřejov Observatory in Czechoslovakia and I examined the large-scale patterns of such fields. We found that although individual magnetic features rotate at different rates depending on latitude in approximately the same way that sunspots do, the rotation of the overall pattern of the fields does not change with latitude over long periods of time and over a large range of latitudes. A few years later John M. Wilcox of Stanford and I confirmed these results and put them on a more quantitative basis. We found that the rigidly rotating patterns persist for many years. They are associated with interplanetary magnetic fields that have been measured near the earth, and they may represent a deep-seated magnetic framework of the sun.

William Henze, Jr., and Andrea K. Dupree of the Harvard College Observatory have measured the rotation of the sun with an experiment aboard *OSO-6* (the sixth Orbiting Solar Observatory). They observed the chromosphere and the corona in the light of spectral lines in the extreme ultraviolet region of the spectrum. Such photographs are roughly similar in appearance to the picture of the chromosphere made in the light of the hydrogen-alpha line, but the ultraviolet emission originates at higher elevations in the sun's atmosphere than the hydrogen-alpha emission. The data from *OSO-6* have yielded rotation rates that are somewhat slower than the rates derived from the other features I have mentioned. Curiously these rates, at least at low latitudes, closely resemble those derived from observations of the Doppler shift of spectral lines.

The wavelength at which a spectral line is formed depends on a transition between energy levels that is characteristic of the emitting species of atom. The wavelength at which the line is observed, however, depends further on the velocity along the line of sight of the source with respect to the observer. If the source and the observer are approaching each other, all the wavelengths will be shifted toward the blue end of the spectrum; if they are receding from each other, all the wavelengths will be shifted toward the red end. Thus a spectroscope aimed at a part of the sun that is turning toward the observer will detect lines that are shifted slightly toward the blue, and an instrument aimed toward a part that is turning away from the observer will detect lines that are shifted slightly toward the red. It is these Doppler shifts that can in principle be used to measure the speed of rotation of various regions of the sun.

The first Doppler-shift measurements of the sun's rotation were made by the German astronomer Hermann Vogel in 1871. Following on his work there were numerous other determinations, all of them plagued by the fact that when a spectroscope was aimed at the edge of the sun, light was scattered into the instrument from the sun's brighter central portion. The spectral lines of the scattered light blended with the lines from the region being observed and tended to




**ROTATION RATES OF MARKERS DIFFER from the rotation rate of the gas of the sun's photosphere, or visible surface, as well as differing with latitude. Since all the tracers are associated with magnetic fields, this fact is interpreted to mean that the sun's magnetic field rotates slightly faster than the gaseous body of the sun itself. The rate of rotation for each marker is given in degrees per day of longitude on the sun. A curve showing what the rotation rate of the sun would be if it behaved as a solid body is given for comparison.**

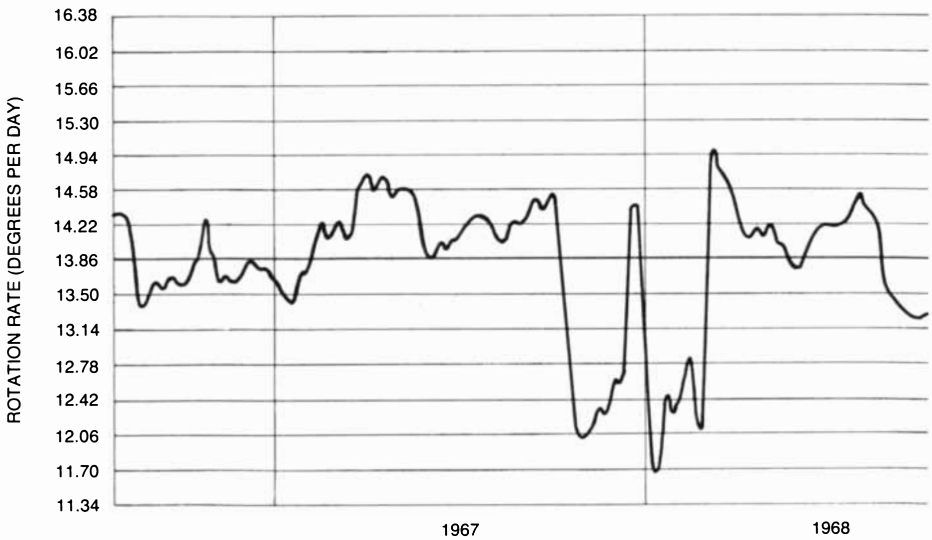
make the measured rotational velocities too low.

In 1966, however, measurements were undertaken with the solar magnetograph on Mount Wilson, a photoelectric scanning spectrometer. Actually measuring the rotation of the sun with this instrument was a by-product of an effort to monitor the magnetic fields of the sun. The solar magnetograph is so sensitive that it can detect a difference in velocity along the line of sight as small as 10 meters per second (a figure that happens to be equivalent to the top speed of a human sprinter). With such sensitivity it is now possible to measure the rotation of the sun close to the center of the solar disk, where the scattered-light problem is not as severe as it is at the disk's edge. Since 1966 the rotation of the sun has been monitored daily at Mount Wilson, and these observations constitute the bulk of the spectroscopic rotation data now available.

During the total solar eclipses of 1970 and 1973 John W. Harvey, William C. Livingston and L. Doe of the Kitt Peak National Observatory measured the rotation of the corona with spectroscopic techniques. They studied the coronal green line, which originates with iron atoms that have been stripped of many of their electrons by the corona's high temperature. These measurements showed little evidence that the corona's rate of rotation varies with latitude, although their accuracy is somewhat limited by the fact that parts of the corona also move randomly at substantial velocities.

The average rotation of the sun as a function of latitude, derived from various studies, is shown in the illustration at the left. In general the studies of the equatorial rotation velocity can be divided into two groups: the spectroscopic results and everything else. The sunspots, the filaments, the bright coronal streamers and the photospheric magnetic fields rotate approximately one day per rotation faster than the photosphere does. These fast-moving features have one thing in common: they are all associated with magnetic fields in the solar atmosphere. Sunspots have strong magnetic fields, filaments are known to lie between magnetic regions of opposite polarity and coronal streamers correspond to looping lines of magnetic force in the corona.

It thus appears that the magnetic fields rotate somewhat faster than the bulk of the photospheric gas does by about one day per rotation, or about 75 meters per second. (The rotation speed of the photospheric gas at the equatorial latitudes of the sun is about two kilometers per second.) It is possible, although it is by no means universally believed by solar physicists, that the magnetic fields rotate more rapidly than the photospheric gas does because they are connected to certain interior layers of the sun whose rotation rate is also fast. The magnetic fields, which are generally confined to tightly packed lines of force occupying only a small fraction of the surface area of the sun, can move




**ROTATION RATE OF THE SUN VARIES with time as well as with latitude. That variation is shown by this illustration of the sun's equatorial rotation rate monitored over a**

through the solar atmosphere like the periscopes of a fleet of submarines plowing through the ocean.

The rates of rotation of the visible features of the sun not only differ from the rate of the photosphere but also differ slightly from one another, depending on their latitude. Such differences are puzzling and for the present have no explanation. The uncertainties in the measurements of most of these rates increase at higher latitudes, and it is possible that at least some of the discrepancies are caused by systematic errors. By the same token slight differences in the spectroscopically measured rotation rate of the photosphere in the northern and southern hemispheres of the sun are near the limit of detectability, and for now they too must be set aside as possibly resulting from systematic errors.

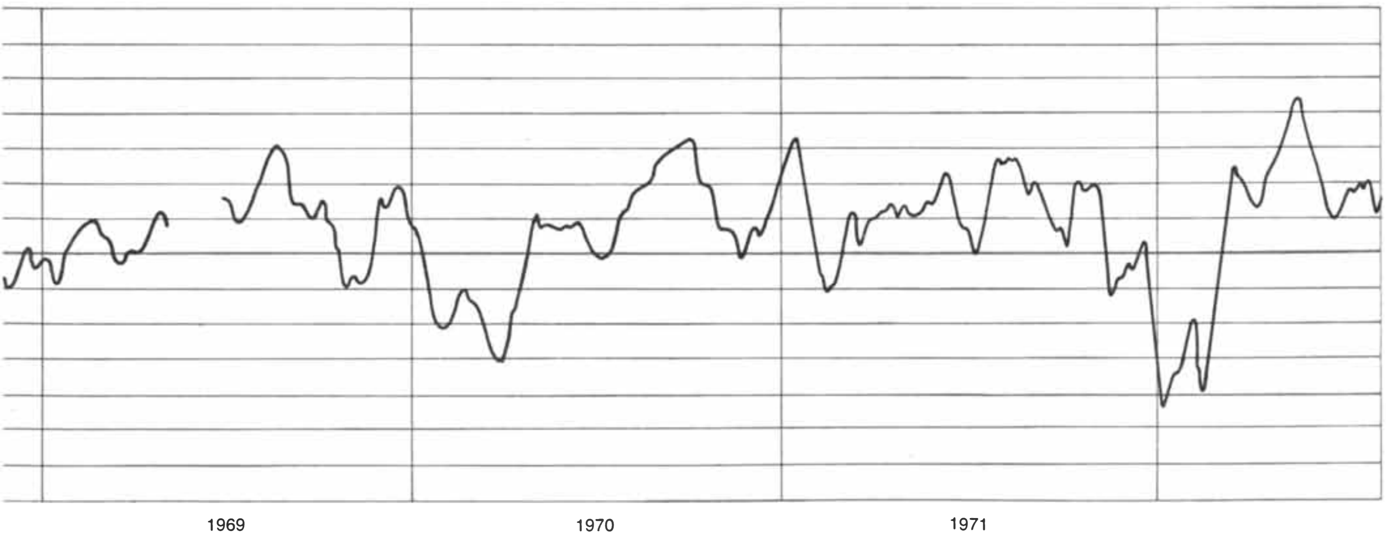
Spectroscopic observers early in this century generally agreed that the gases at higher altitudes in the solar atmosphere rotated significantly faster than those lower down. This view has since been discredited, not only because it seems highly unlikely but also because Livingston and Robert W. Milkey at Kitt Peak have recently made accurate observations that show it is untrue. They attribute the erroneous earlier results to the fact that in the spectra some of the absorption lines in the solar atmosphere blended with weak lines due to molecules in the earth's atmosphere, distorting the measurements.

Spectroscopic determinations of the rate of the sun's rotation have shown that it changes frequently. Over weeks or months the equatorial rotation rate may vary from the average by as much as 5 percent. These variations could be correlated with short-term variations in some aspect of solar activity, such as the number of sunspots, the mean strength of the magnetic fields or the frequency of solar flares. The first attempts to demonstrate such associations, however, have yielded no positive results. Over the past few years the spectroscopic data from Mount Wilson have shown a general tendency for the rotation rate to increase as solar activity has declined from the most recent maximum of the 11-year solar cycle in 1969. The increase has been only a few percent, and under the circumstances it is premature to conclude that there is a firm relation between the sun's rotational velocity and the phase of the solar cycle. Nevertheless, there is a strong possibility that such a connection exists, and solar observers will be examining the rotation rate with great care as the next maximum of the solar cycle approaches.

As yet there is no generally accepted theory as to why the sun's rotation should vary with latitude. The differential rotation, or any other large-scale phenomenon on the sun's surface, must be intimately related to the sun's internal structure and to the dynamics of the convective zone in its interior. The convective zone has a thickness equal to about 20 percent of the solar radius, and its upper boundary lies just below the layer of the photosphere where most of the spectral lines we see are formed. The gas in the convective zone comprises less than 1 percent of the total mass of the sun. Most of the mass is concentrated in the sun's dense, hot core, where thermonuclear reactions release the energy that is ultimately radiated from the photosphere. The energy is transmitted from the core up to the convective zone by means of radiative processes, that is, atoms within the sun absorb radiation and then reemit it. In the outer 20 percent of the sun's radius, however, the gas becomes unstable. Convective motions result, and almost all the energy in this region is transported by convection: hotter gases rise and cooler gases sink.

When we observe the sun, of course, we see only the layers of the photosphere above the convective zone. All that we know about the structure of the solar interior is inferred from the sun's mass, its surface temperature, its chemical composition and our theoretical knowledge of nuclear processes and the physical behavior of gases. We have no means of directly observing the rotation of the solar interior. Robert H. Dicke and his collaborators at Princeton University have nonetheless advanced a hypothesis about this rotation on the basis of their careful measurements of the sun's oblateness.

From the observed fact that the sun rotates once every 27 days one would predict that its poles would be flattened by about .01 second of arc out of the sun's apparent radius of 15 minutes of arc, corresponding to seven kilometers out of the sun's average radius of 700,000 kilometers. Such a minute quantity is very difficult to measure accurately because it is at least 100 times smaller

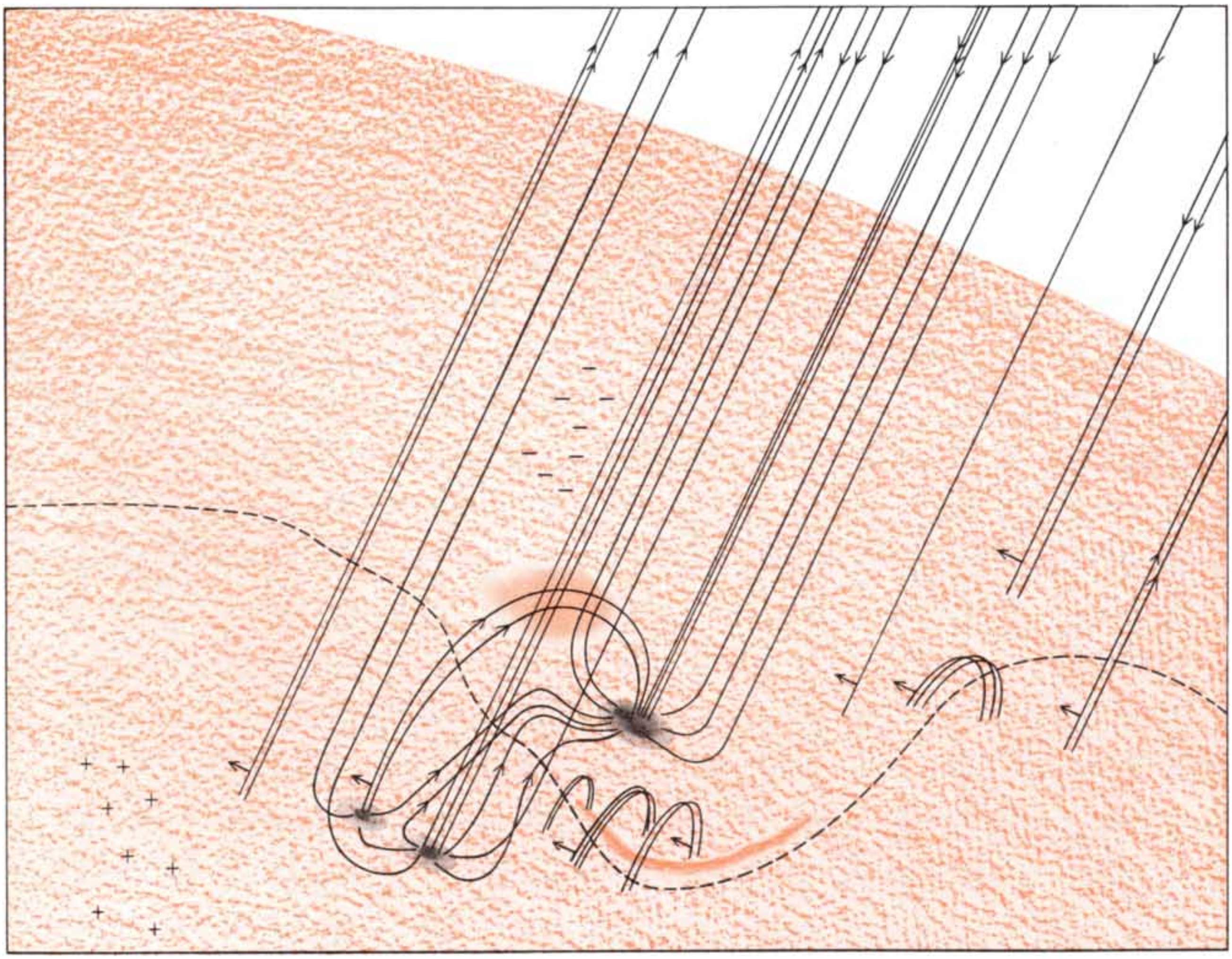



**period of six years. The rate is plotted in degrees of longitude on the sun per day. The horizontal line at 13.86 degrees per day represents the average equatorial rotation rate over this period. Sometimes the rate varies suddenly for reasons that are not fully known.**

than the blurring effects of the turbulence of the earth's atmosphere on the image of the sun. It is also smaller than errors introduced by imperfections inherent in the optical systems used to study the sun. In spite of these obstacles Dicke, working with an instrument of ingenious design, has measured the sun's shape and has concluded that its oblateness is five times as large as one would predict, namely about .05 second of arc. This relatively large oblateness, he explains, is due to the rapid rotation of the central core of the sun: about one turn per day. Such a rapidly rotating core will itself be oblate and will slightly alter the gravitational field at the surface of the sun, so that the surface too will be slightly oblate. Dicke's work has stimulated a controversy that has not yet been resolved. Recent attempts by another group have failed to confirm his results.

If the core of the sun is rotating rapidly, it cannot be tightly coupled to the convective zone. Ionized atoms are electrically charged particles that "feel" a magnetic field, and in a highly ionized gas such as the one that makes up the sun the lines of magnetic force can be considered to be mechanically coupled to the constituent atoms. Therefore if the lines of magnetic force are moving as the sun rotates, they will drag the ionized gas along with them. And if the lines of magnetic force thread their way from the sun's core through the convective zone, the two zones cannot maintain very different rotation rates for very long. In addition any exchange of material between a rapidly rotating core and a slowly rotating outer envelope will transfer momentum to the outer envelope and tend to decrease the difference in the two rotation rates.

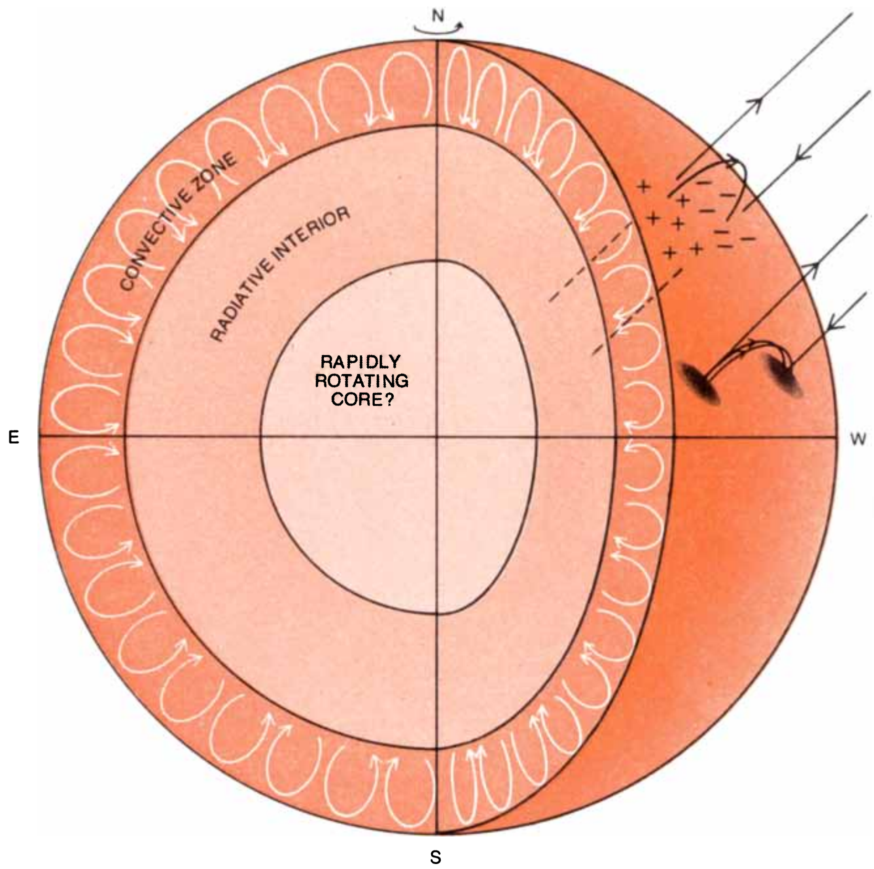
Within the convective zone itself angular momentum is transferred easily and quickly in the radial direction by the continual convective motions. Moreover, the "wind" of solar particles that is constantly streaming away into space along the lines of force in the sun's magnetic field exerts a dragging effect that is strong enough to stop the rotation of the convective zone in only one million years. A million years is a short time on the scale of cosmic events, and we know the sun's surface layers cannot be decelerating that rapidly. If they were, and if the deceleration rate had remained constant for some time, only a few hundred million years ago the sun would have been rotating so fast that it would



**MAGNETIC FIELD LINES** *(black)* **at the surface of the sun** *(color)* **are confined to sunspots and to small bundles of lines outside spots. They are always closed loops, originating at the side of the sun with positive polarity and looping over a narrow neutral region** *(broken line)* **into an area of negative polarity. The long field lines extend far out into interplanetary space before they loop back to the surface. The small arrows at the base of the field lines show that they rotate about 75 meters per second faster than most of the photospheric gas; the gas not directly connected with a magnetic feature simply allows the lines to pass through. Ill-defined region centered on the field lines between sunspots is a coronal enhancement; above it streamers of the corona are particularly prominent.**

have thrown off an appreciable fraction of its mass by centrifugal force. Since the dragging force of the solar wind is not strongly slowing the rotation of the convective layer, much of the force must be expended in slowing the denser matter below the convective layer, although not necessarily the matter in the core.

In this general picture the lines of force in the sun's magnetic field are firmly connected to deeper layers of the sun where the rotation rate is higher than it is at the surface. The lines of force are dragged through the photosphere by their roots, although the depth of these roots has not been established. An alternative explanation for the difference between the rotation rates of the magnetic fields and the rotation rate of the photosphere is that there is a large-scale pattern of circulation in the sun that somehow (it is not clear exactly how) moves the field lines preferentially in one direction. On a small scale of perhaps 1,000 kilometers there is a circulation pattern on the solar surface called granulation, and on a slightly larger scale of about 30,000 kilometers there is a pattern called supergranulation. George W. Simon of the Sacramento Peak Observatory has suggested that there might be an analogous pattern on a scale of about the radius of the sun. Observational evidence for such a giant circulation pattern is skimpy, but perhaps that is not surprising, because the velocity of the flows in such a pattern is expected to be quite low—only a few meters per second.



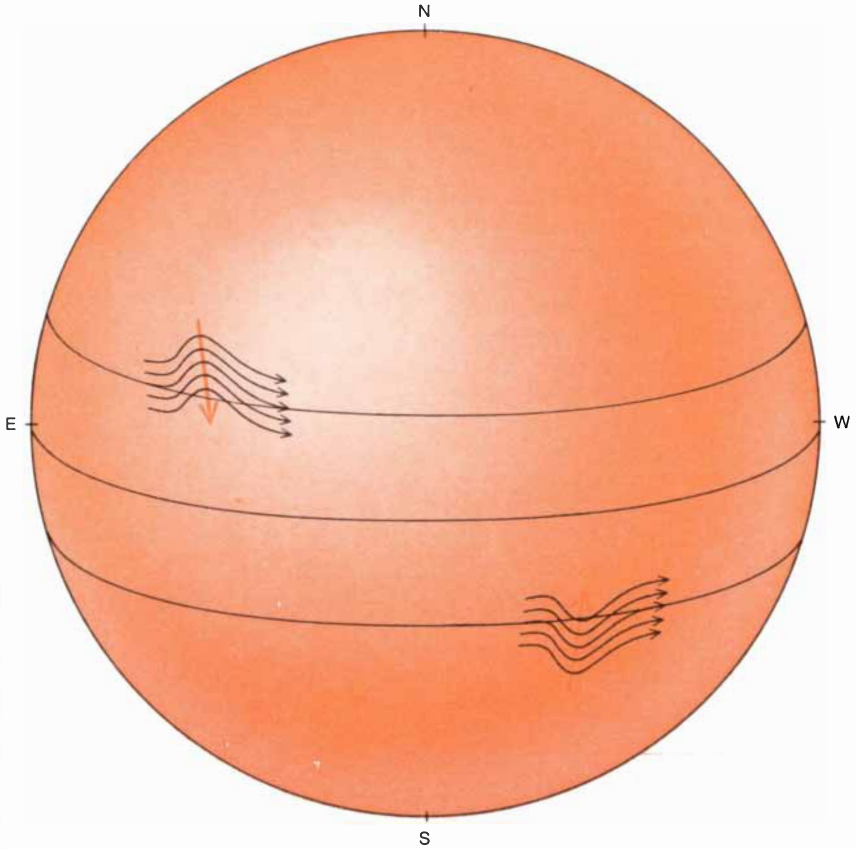

**INTERIOR OF THE SUN in this cutaway view shows the convective zone and the hypothesized rapidly rotating core. The sun's energy is generated by thermonuclear reactions in the core and is transported toward the surface by means of radiative processes: atoms of the gas absorb, reemit and scatter the radiation. At a point about 20 percent of the radius from the surface the gas becomes unstable to motions along the radius and the energy is transported by convection: hot gases rise and cool gases fall. The roots of the magnetic field lines extend through the convective zone, although the depth to which they reach is not known. The lines that extend into interplanetary space carry with them a steady flow of ionized gas: the solar wind. Entire pattern of the magnetic fields rotates with the sun, and the effect of the solar wind is to exert a drag on rotation of outer layers of sun.**

There are several theoretical models that attempt to explain why the angular velocity of the sun varies with latitude. None of these models, however, is based on exact solutions of all the physical equations involved. Solar physics suffers from the lack of a definitive theory of turbulent convection in a compressible gas. The models I shall discuss are for the most part ingenious combinations of solutions for large-scale motions in simplified physical cases and assumptions about the large-scale effects of small-scale processes.

Ludwig Biermann of the Max Planck Institute for Physics and Astrophysics in Munich has suggested that if the viscosity of the convective gas in the sun is not the same in all directions, the result can be differential rotation. Biermann's colleagues have extended this notion into a more refined model. If the viscosity of the solar gas in the radial direction is less than that in the plane perpendicular to the radial direction, the convective circulation patterns result in a net transport of angular momentum toward the solar equator because the gas moving radially toward the equator carries more angular momentum than the gas moving radially toward the poles. Hence the energy maintaining the high equatorial rotation rate comes from the convective motions. One disadvantage of this model is that it requires the inner layers of the sun to rotate slower than the outer layers, whereas the evidence from the rotation of the magnetic tracers points to the opposite conclusion.

A second model, first suggested by Fred W. Ward of the Air Force Cambridge Research Laboratories, posits that there are surface circulation patterns in the solar atmosphere that are analogous to patterns in the earth's atmosphere known as Rossby waves. Such patterns would transport angular momentum toward the solar equator because of the way in which the waves are slanted [*see illustration on next page*]. The waves moving toward the equator carry more angular momentum than the waves moving toward the poles, and thus the waves moving toward the equator support the faster equatorial motion. Here one considerable problem remains: to explain why the waves exist and how they are maintained. One suggestion is that they are maintained by a temperature gradient on the sun: the poles are hotter than the equator. Such a temperature gradient has not been observed. Recently, however, a wave pattern similar to the one required for this model has been detected by R. G. Hendl of the Massachusetts Institute of Technology on the basis of the observations made at Mount Wilson, lending support to the Rossby-wave hypothesis.

A third model relies on the notion of the giant convection cells. According to




**ROSSBY WAVES is one model proposed for explaining why the sun rotates differentially. The curved arrows of the Rossby waves (*gray*) are streamlines, representing the motion of the gas on the sun's surface. Because of the shape of the streamlines the motion of the gas toward the equator (*arrows in color*) carries more angular momentum (momentum of rotation) toward the equator than toward the poles. The net effect is to transfer momentum.**

theoretical calculations made by B. R. Durney and Peter A. Gilman at the National Center for Atmospheric Research, the sun is likely to generate large-scale convective circulation in long rollers that move predominantly from east to west near the surface. The rollers can transport momentum to the equator if their motions are not exactly east to west. This model has had some success in reproducing some of the characteristics of the sun's differential rotation. It suffers, however, from the disadvantage that it too calls for a lower rotation rate below the surface than at the surface. An additional disadvantage is that a sizable flow from north to south is also needed to make the model work. Although some observers, notably H. H. Plaskett of the University of Oxford, have reported detecting such motions, sensitive observations made at Mount Wilson do not confirm their existence.

K. H. Schatten of the Victoria University of Wellington in New Zealand has suggested that the differential rotation of the sun results not from the acceleration of the equatorial region but from the deceleration of the regions at higher latitudes. He argues that the lines of magnetic force extending into interplanetary space originate preferentially at the high latitudes, so that the dragging effect of the solar wind will slow those regions more. Hence it is not necessary to transfer angular momentum to the equator because it is automatically extracted from the high latitudes.

At the moment it is not possible to say which, if any, of these models gives the correct explanation. The fertile minds of theoreticians seem able to devise many mechanisms to explain the differential rotation of the sun. When the explanation is known, it will greatly assist our understanding of the structure and rotation of the solar interior and, through the connecting medium of the magnetic fields, our understanding of solar activity. Moreover, since the sun is a Rosetta stone for learning about the billions of other stars in the universe, the explanation will also aid investigations into the nature of stars and into the evolution of the galaxy.

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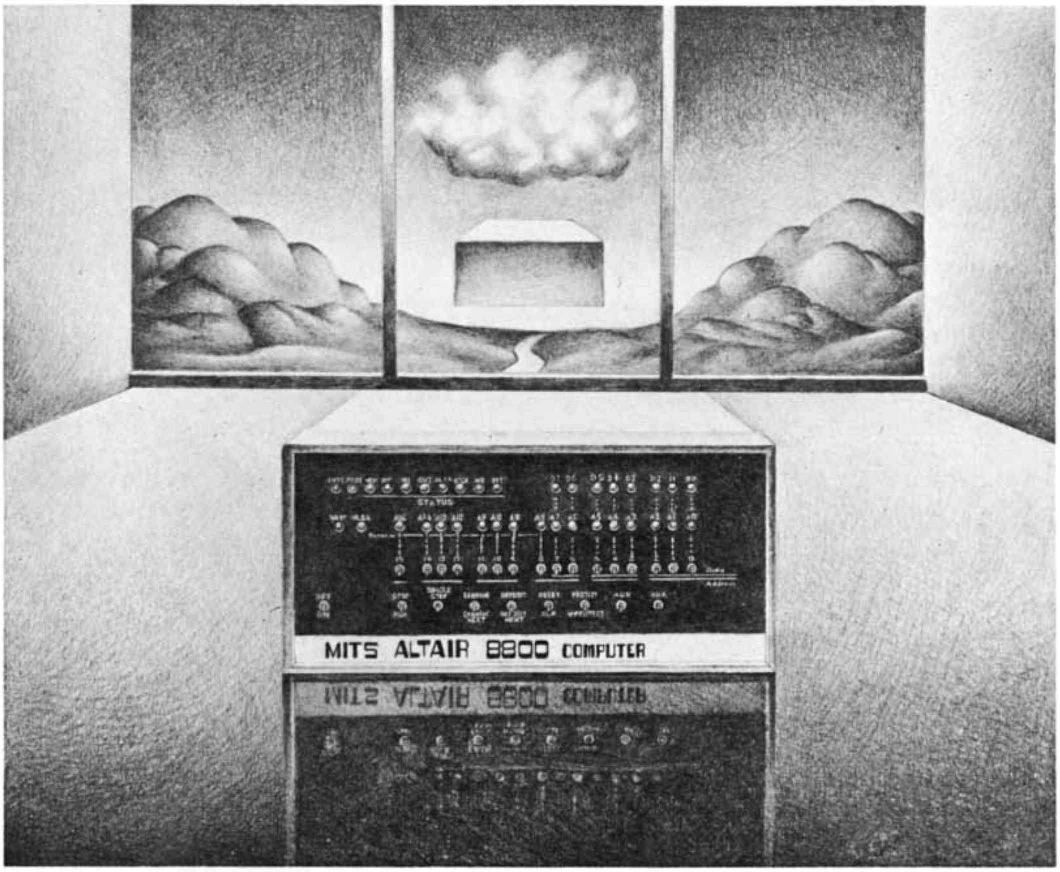


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# The Deformation of Metals at High Temperatures

*The hot-working of metals was long more an art than a science. The study of how metals behave at the level of atoms in crystal lattices is doing much to put the art on a more rational footing*

by Hugh J. McQueen and W. J. McGregor Tegart

The blacksmith is an almost legendary figure now, standing by his glowing fire and hissing bellows as he hammers a piece of red-hot iron into shape with skillful blows. Today the hot-working of metal is on the scale of a heavy ingot, weighing many tons and being shaped by a huge pneumatic hammer, a hydraulic press or a rolling mill. More than 80 percent of all metal products undergo high-temperature deformation at some stage in their processing. The products are as diverse as seamless tubes, turbine blades, railroad-car wheels, stainless-steel knives, concrete-reinforcing rods and the sheet steel from which many products are made by further working without heating.

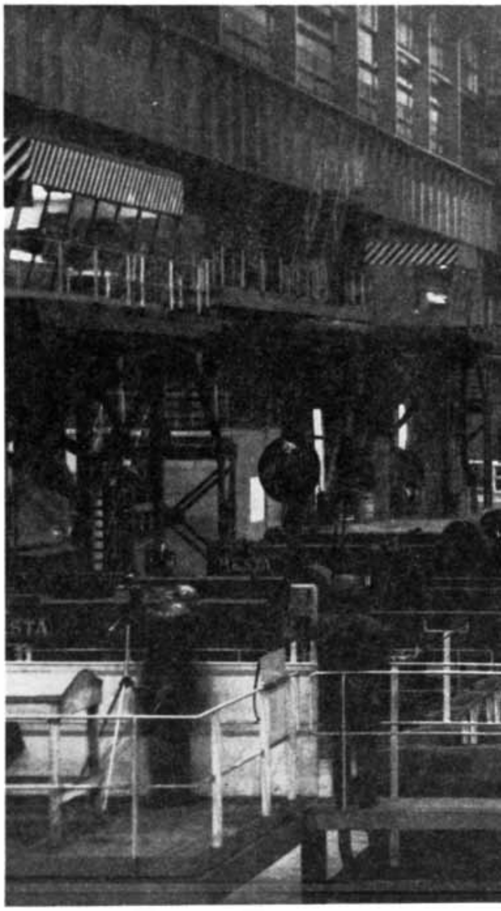
The technique of forging goes back some 3,000 years. For that span of time men have known that metal can be most easily shaped when it is hot. The remarkable thing is that hot-working is still largely an art. Only recently has metallurgy reached the stage where the behavior of the crystals and atoms of a metal during hot-working is understood. The knowledge is so new that it has not yet been widely applied in industry. One can predict, however, that it will be put to use before long, because it holds the promise of providing materials of superior strength and toughness without adding to (and probably with a reduction of) the consumption of mineral resources and energy.

A further achievement of the new knowledge is the confirmation that these mechanisms are similar to the ones that give rise, on a much slower time scale, to the problems of creep and relaxation. These problems became troublesome a little more than a century ago as steam engines were brought into wide use. It was observed that after prolonged service the tubes of boilers expanded, stretched and sagged. A much older example of such behavior is the loosening of the lead strips between windowpanes. This slow elongation and eventual fracture of metals under constant tensile stress at high temperature became known as creep. Relaxation was the tendency of rivets and tight bolts in steam engines to loosen gradually, giving rise to leaks. Now that the atomic mechanisms responsible for creep and relaxation are better understood, the means are at hand to make metals that resist those fates more effectively.

As is frequently the case in science, the atomic mechanisms of high-temperature deformation were determined only after research had been done and theories had been developed on simpler processes. They include cold deformation, slip by dislocations, recrystallization and recovery. Let us describe these mechanisms in order to lay a foundation for our discussion of high-temperature deformation.

Cold deformation is probably the most characteristic and most appreciated property of metals. The term describes the ability of metals to change shape at ordinary ambient temperatures. The property is exploited by anyone who fits a sheet of aluminum foil around a roast, bends a wire or straightens the fender of an automobile. Industrial cold-working processes include the drawing of rod into wire, the rolling of threads onto bolts and the forming from sheet metal of products ranging from cooking pots to automobile bodies.

This property of metals seems even more remarkable when one considers that a piece of metal consists of innumerable tiny crystals in different orientations, much as a sandstone consists of sand grains bonded together. As was first demonstrated by Henry Clifton Sorby in England in 1864, the grains of a metal can be observed by etching a polished metal surface with an acid solution,



**SLAB OF HOT STEEL** emerges from heavy rollers in a forming operation at the Gary which rapidly attacks the boundaries of the grains [*see top illustration on next page*]. Within a grain, or crystal, the atoms are in a regular array and in their lowest energy state. Between grains is a layer about two atoms thick in which the atoms are in a higher energy state.

When the metal is deformed, as for example by rolling, the roughly spherical grains are squashed into pancakes, which are elongated in the direction in which the metal is rolled out [*see illustration on page 119*]. During this period of plastic strain a continuous bond is maintained across the grain boundaries. As the grains become distorted the flow stress (the force per unit of area) required for further strain (the deformation per unit of length) rises. Ordinary steel yields plastically at a flow stress of about 25,000 pounds per square inch and hardens to a strength of about 100,000 pounds per square inch at a strain of .8. (Units of strain reflect the relation between the change in dimension and the initial dimension of the metal being deformed.) One can see the hardening effect by bending a thin rod at a sharp angle; straightening the kink thereafter is extremely difficult.

A satisfactory theory of these effects must explain two things. One is the mechanism whereby the grains deform without either cracking or losing their crystalline structure. The other is the cause of the strain hardening.

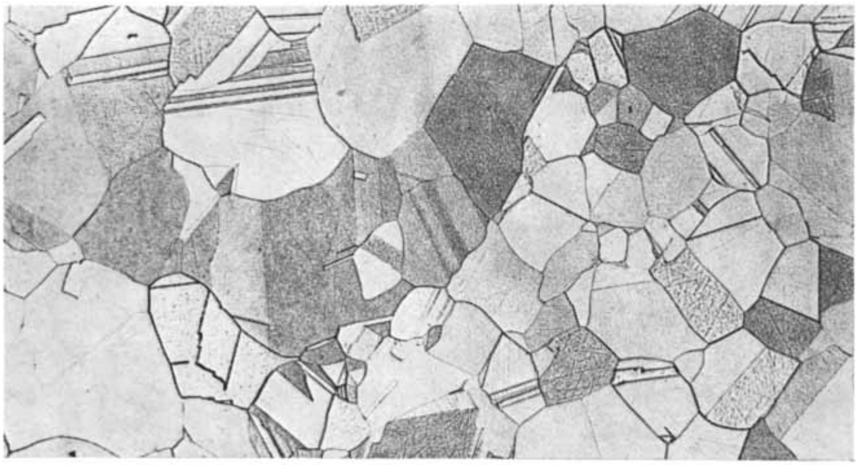
The theory that provides these explanations deals with slip and dislocations. Within a crystal deformation occurs when half of the crystal shears along the other half; this is the phenomenon called slip. The shearing takes place along a slip plane. Each crystal usually has several nonparallel sets of slip planes; they are the regions in the crystal that have the least resistance to shear.

Nonetheless, the shear stress that is sufficient to cause yielding is too low to shear the entire plane all at once. An explanation for this discrepancy was proposed in 1934 by Geoffrey I. Taylor and Michael Polanyi in England and Egon Orowan in Germany. It was that slip takes place as a ripple of shear sweeps across the plane. (A wrinkle in a rug demonstrates the same principle: one can push it toward a parallel edge, thereby changing the position of the entire rug.) As the ripple passes it displaces the atoms on one side of the plane one atomic spacing with respect to those on the other side.

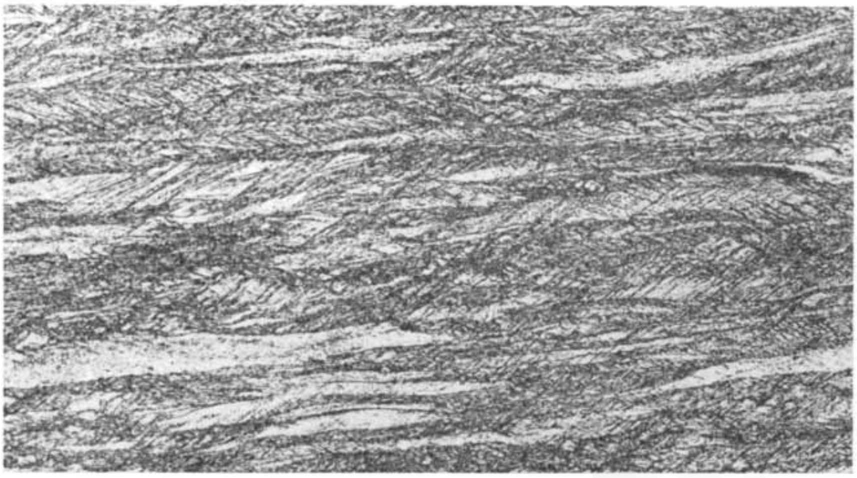
The ripple constitutes a continuous geometric dislocation in the lattice of atoms in the crystal, and it creates a long-range elastic distortion, that is, a displacement of the atoms from their equilibrium positions. Although a dislocation can extend in any direction in a crystal, in two orientations the atoms around it have simple geometric arrangements. An edge dislocation, which is perpendicular to the shear vector, looks like an extra half plane of atoms terminating at the slip plane [*see illustration on page 120*]. A screw dislocation is parallel to the shear vector; it appears as the axis of a spiral ramp. A dislocation winding through a crystal can change orientation many times.

An edge dislocation can glide along the slip plane. It can also climb perpendicularly to the slip plane as atoms leave the bottom of the half plane to fill vacant sites in the lattice or join the bottom of the half plane, creating vacancies. A screw dislocation can glide along any slip plane that includes the slip vector; thus it can cross-glide from one plane to

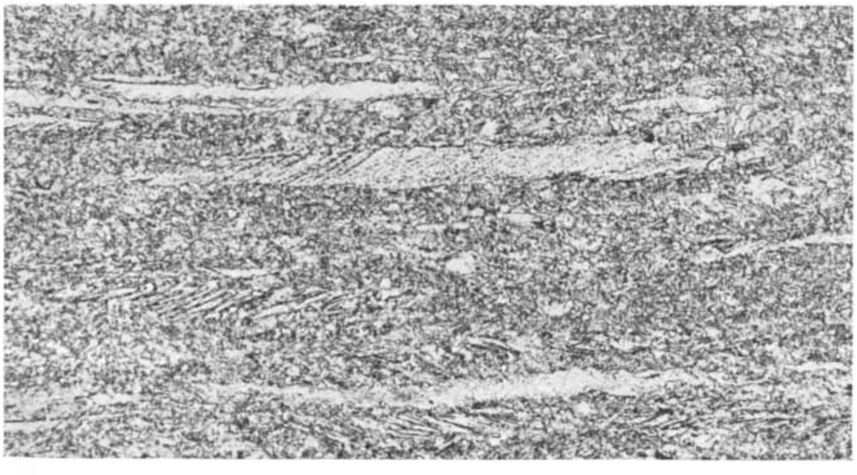
**Steel Works of the United States Steel Corporation. This mill can roll plates of from 30 to 200 inches in width and from 3/16 inch to 15 inches in thickness. Rolling is the major method of working hot metal in terms of both tonnage and variety of products made.**



**UNDEFORMED BRASS** appears in a micrograph that shows its grains, or crystals, as rounded polygons. The grains are three-dimensional, being rounded irregular polyhedrons that fit together without gaps. The different orientations of the grains are evident in the micrograph as different shadings. The enlargement of the micrograph is about 250 diameters.



**ELONGATED GRAINS** appear in brass after it has been deformed by cold-rolling to a decrease in thickness of 75 percent. Distortion of the crystal lattice makes each grain stronger.



**ANNEALED BRASS** has undergone partial recrystallization. Annealing involves heating and then recooling metal after cold-working. In this case the annealing was for about eight minutes at a temperature of 400 degrees Celsius. Annealing restores some of the ductility of the metal by giving rise to new grains through recrystallization. If annealing were continued for a sufficient time, the grains would grow to the size of the ones in unworked metal.

another. Dislocations that produce opposite shears cancel out, that is, they annihilate each other when they come together.

How, then, does strain give rise to hardening? When the plastic yield stress is exceeded, many dislocations are created at the grain boundaries, and the dislocations that were already in the crystal multiply. To produce a strain of .1, which is equivalent to an elongation of 10 percent, about 10 million dislocations must glide across slip planes in each cubic centimeter of crystal. As they glide they are hindered by interaction with other dislocations, so that an increasing stress is needed to move them past one another and crowd them closer together. This crowding is the same thing as hardening—a kink that can be straightened only with difficulty.

In a cube of crystal 10 microns on an edge the original dislocations have a total length of about 10 microns, meaning that the dislocations are spaced about 100,000 atoms apart. A strain of 2.3, which is equivalent to rolling to a reduction of 90 percent, produces some hundreds of meters of total dislocation length. The spacing of the dislocations is reduced to about 100 atoms.

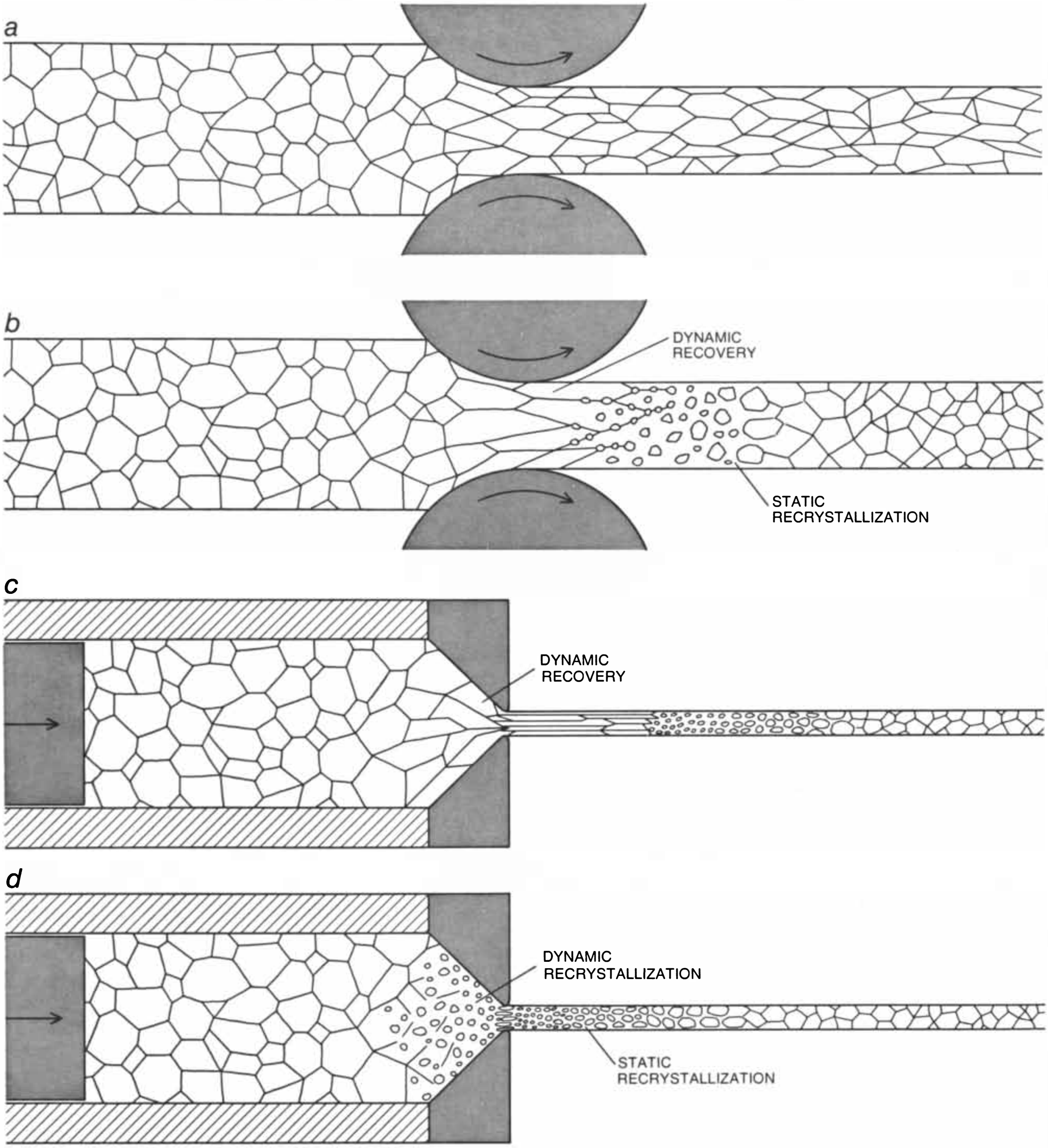
The observation of dislocations in the electron microscope, first achieved some 20 years ago by P. B. Hirsch and his colleagues in England, revealed that the initial dislocations form a loose network. As a result of deformation the dislocations array themselves in a pattern that is characteristic of the metal or alloy. The pattern ranges between two extremes.

At one extreme, represented in brass and bronze, the dislocations are arrayed in planes. The dislocations are piled up one behind the other on their slip planes, much like automobiles caught in a traffic jam on a gigantic grid of streets. As strain is increased the dislocations are packed closer and closer and tend to interact more strongly.

At the other extreme, represented in aluminum and iron, the dislocations are tangled in dense walls like winding and intersecting hedges. The walls divide the crystal into cells, within which there is a residual loose network of dislocations. This cellular structure comes about whenever the dislocations are able to cross-glide as a result of interaction with other dislocations. At that stage deformation proceeds because dislocations are generated at cell walls and move across several cells before they are caught in other walls.

Increased strain makes the cells smaller as new entanglements form, partition-ing the cells [*see illustrations on page 122*]. As the cells approach what appears to be a lower limit of size, dislocations resulting from further strain increase only the thickness and density of the tangles, thus not giving rise to as much strain-hardening. The minimum cell size is about one micron at ordinary ambient temperatures and is somewhat larger when high temperatures make cross-gliding easier.

Although strain-hardening is beneficial in making a metal more resistant to an accidental change of shape while the material is in service, it is disadvantageous in any kind of processing that requires a large deformation or a series of small ones. An example would be drawing rod into wire that is then bent as it is woven into fencing. Fortunately the original softness and ductility can be re-




**ROLLING AND EXTRUSION are portrayed on the scale of grains. In cold-rolling (*a*) the grains are flattened, internally distorted and hardened by strain. They persist until the metal is annealed. In hot-rolling (*b*) with dynamic recovery, meaning that the crystals remain soft without recrystallization, the grains are similarly flattened but are not distorted internally to the same extent. Because the metal remains hot, static recrystallization occurs after deformation. In hot extrusion at a high strain the metals that undergo dynamic recovery do not recrystallize until after deformation (*c*), whereas metals in which recovery is limited recrystallize dynamically during deformation and again statically after deformation (*d*). In most metals the actual size of a grain is from 10 to 1,000 microns.**

stored by annealing, or heating, the worked metal.

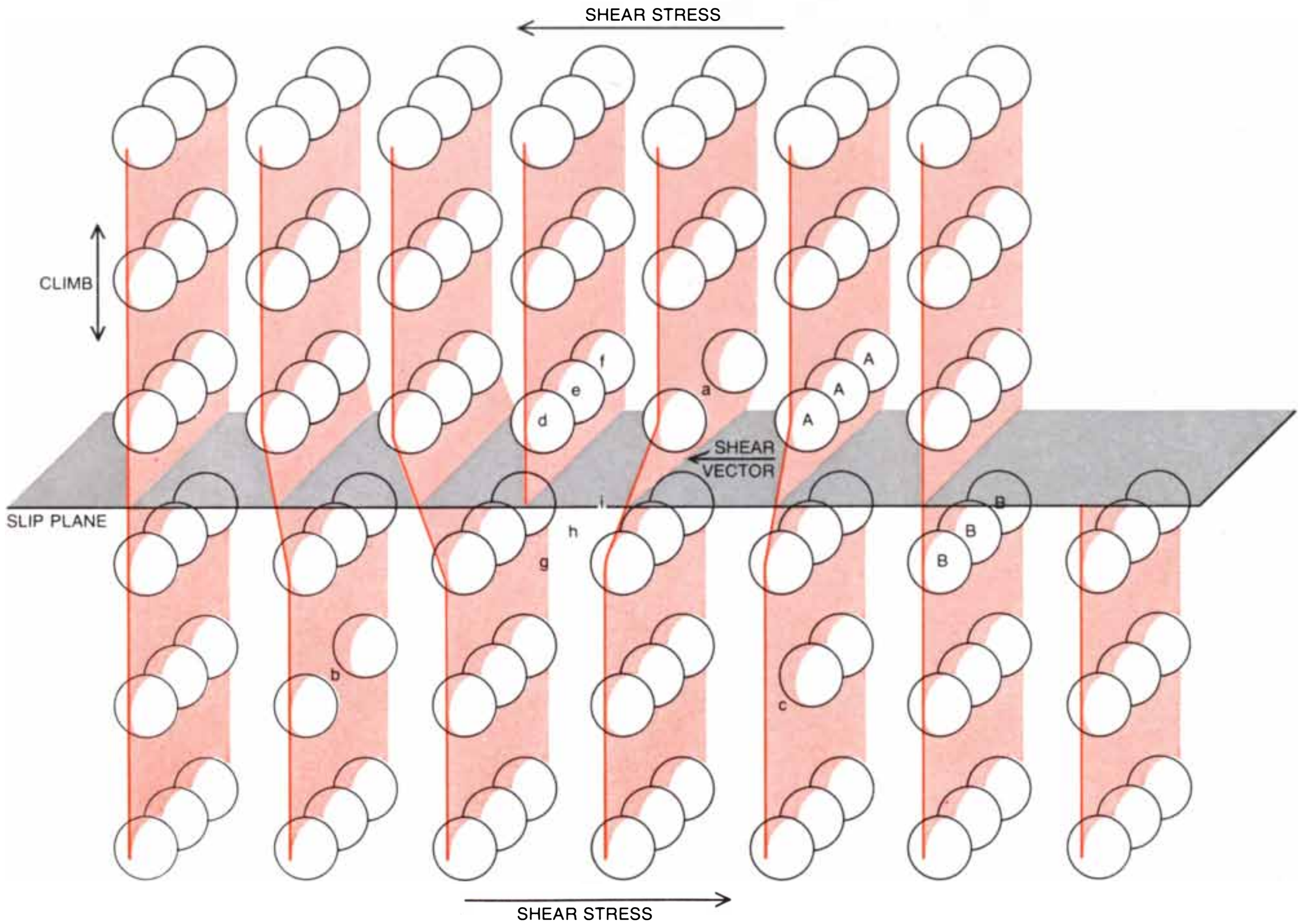
The properties that existed before deformation are restored because in annealing the elongated and hardened crystals are replaced by a completely new set of spherical and soft crystals. This process of recrystallization begins with the formation of exceedingly tiny crystals around crystal nuclei. The new grains then grow because their boundaries migrate into the deformed grains. Atoms from the distorted crystals jump through the boundary and attach themselves to the growing crystals.

When crystals that have been slightly deformed are annealed, they become softer without recrystallization. This process is called recovery. It entails a gradual decrease in the number of dislocations and a rearrangement of the remaining ones into orderly arrays.

The rate of recovery depends on temperature to the same extent as diffusion does, and so recovery appears to involve diffusion. In diffusion atoms intermingle through spontaneous movement resulting from thermal agitation. The rate of diffusion is related to the frequency with which atoms jump into nearby vacant sites in a crystal; necessarily the vacancies migrate in the opposite direction (to the atoms) at the same rate. Therefore the essential mechanism of recovery appears to be the climb of edge dislocations at a temperature high enough for the atoms to have sufficient vibrational energy to enable the vacancies to migrate rapidly. At such a temperature the screw segments of the dislocations can cross-glide readily to accompany the edge segments.

The increased mobility of dislocations at the annealing temperature enables them to move under the attractive forces of other dislocations until they annihilate one another or form into arrays of similar dislocations that have a low energy. Because the dislocations partly cancel one another's elastic distortions, a dislocation decreases its energy as it crowds into an array of edges. The geometry of an array of edges is such that it causes a tilt of a few degrees in the regions on opposite sides. An array of screws produces a twist. In either case the result is a variety of misorientations; since they are small the tilted regions are called subgrains; the arrays are known as sub-boundaries [*see illustration on page 123*].

Deformed metals of the type that has a cell structure soften gradually and to a limited extent by recovery before recrystallization starts. The recovery mechanisms of climb and annihilation slowly change the tangles into neat arrays and the rough cells into subgrains. As the time of annealing is lengthened the subgrains grow larger by the disappearance of some of the sub-boundaries. In many cases the dislocations are attracted into arrays of similar dislocations, thereby increasing the misorientation caused by the array. If this process is continued, particularly in regions that have very dense tangles, some sub-boundaries attain a misorientation of




**DISLOCATION IN CRYSTAL** results from the presence of an extra half plane of atoms in the crystal lattice. Deformation occurs by shearing along a slip plane, which is the plane perpendicular to the extra half plane of atoms. Here, as a result of shear applied from the right, the atoms marked *A* have been displaced with respect to the atoms marked *B* by a length equal to the shear vector. If the vacancies shown at points *a*, *b* and *c* migrate to replace the atoms *d*, *e* and *f*, the dislocation climbs upward to the next slip plane. In the downward climb portrayed here atoms jump to vacant positions at *g*, *h* and *i*, introducing three new vacancies in the positions they left.

more than 10 degrees, becoming grain boundaries that are capable of migrating. The region surrounded by such a boundary is a nucleus for recrystallization.

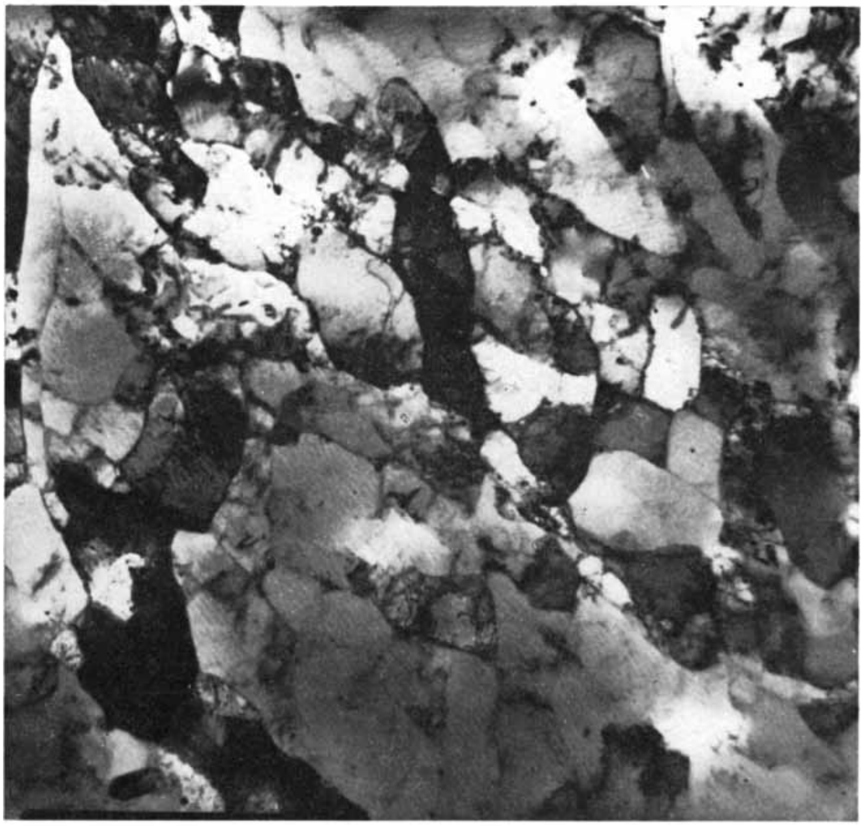
Metals of the type that have two-dimensional arrays of dislocations do not noticeably recover either with respect to a decrease in strength or with respect to the formation of subgrains. Apparently the dislocations in certain areas are so densely packed that they rapidly combine into segments of grain boundary, giving rise to a recrystallization nucleus. In both types of metal recrystallization can also arise from the migration of small bulges in the original grain boundaries.

All the mechanisms we have described figure in the microscopic events of hot-working. The scientific understanding of what happens on the atomic scale during deformation at high temperatures and high rates of strain has progressed in less than 20 years from vague hypotheses to a sophisticated theory founded on evidence from diverse and ingenious experiments. It is now clear that metals in which the dislocations can easily leave the slip planes deform with little hardening as a result of dynamic recovery, that is, recovery that takes place during the deformation.

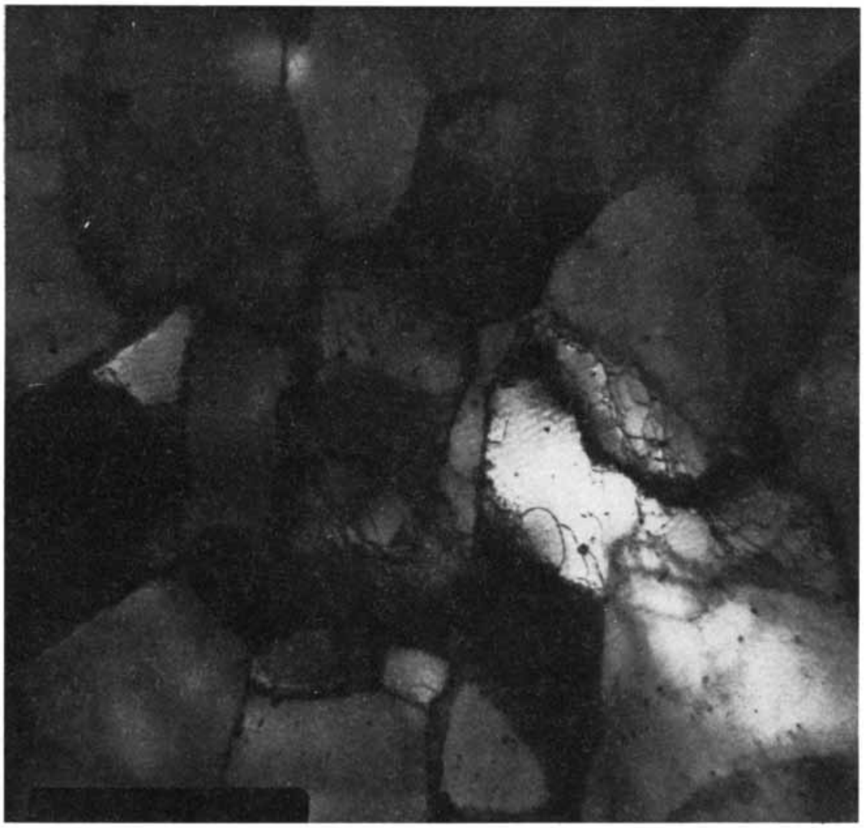
In the course of a typical hot-working deformation at a given temperature and strain rate the dislocations glide, climb, multiply and combine into tangles. The result is that a rising amount of stress is required to maintain flow. As the density of the tangled dislocations goes up, the annihilation of the newly generated dislocations becomes more frequent. When the rates of annihilation and generation balance, the flow stress ceases to rise and deformation proceeds at a steady rate.

Research conducted by John J. Jonas, Winston A. Wong and one of us (McQueen) has shown that in aluminum the subgrains remain constant in size and in wall density at strains of up to 3.4. Moreover, they remain equiaxed, or roughly spherical, even though the grains that are made up of them elongate to 10 times their initial diameter. These findings indicate that although subgrains of fixed size exist at any strain during a steady state of deformation, they are not the same subgrains. In other words, the sub-boundaries are continually broken down by repeated annihilation, but new ones form elsewhere, and their spacing remains constant.

Deformation at a higher temperature results in more rapid annihilation, so that the steady-state balance is reached at a larger subgrain size and thus at a lower



**SUBSTRUCTURE OF ALUMINUM** is displayed after cold-working. It consists of small cells that are outlined by dense tangles of dislocations. The enlargement is 12,800 diameters.



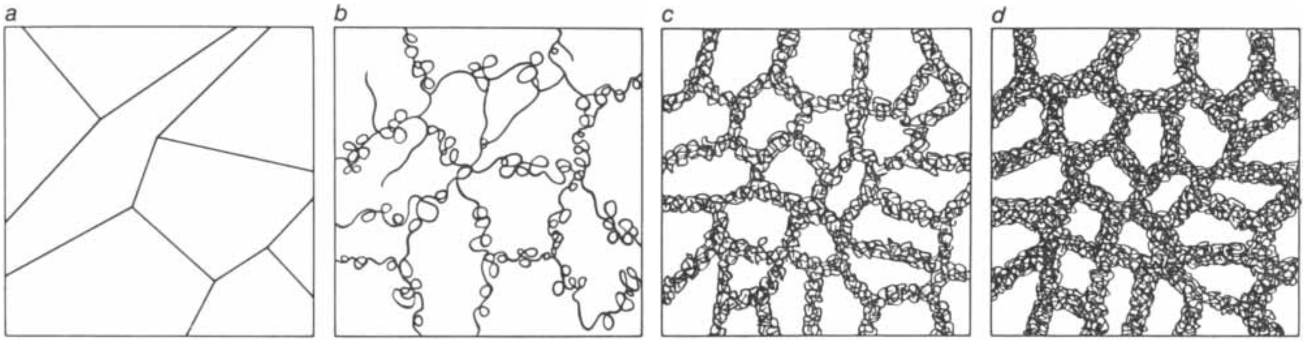
**HOT-WORKED ALUMINUM** shows a different substructure, consisting of large cells or subgrains having fairly orderly sub-boundaries. The working temperature was 400 degrees C. The micrographs on this page were made with the transmission electron microscope.

flow stress. On the other hand, deformation at a higher strain rate results in more rapid generation of dislocations, and the steady-state balance is reached at a smaller subgrain size and a higher flow stress. These observations, along with those of subgrains produced by creep, make it possible to formulate a quantitative relation between flow stress and subgrain size. (In creep the subgrains are from five to 10 times larger because the stress and the strain rate are much lower. The extensive research results from the field of creep have been of considerable assistance in interpreting the observations of hot-working.)

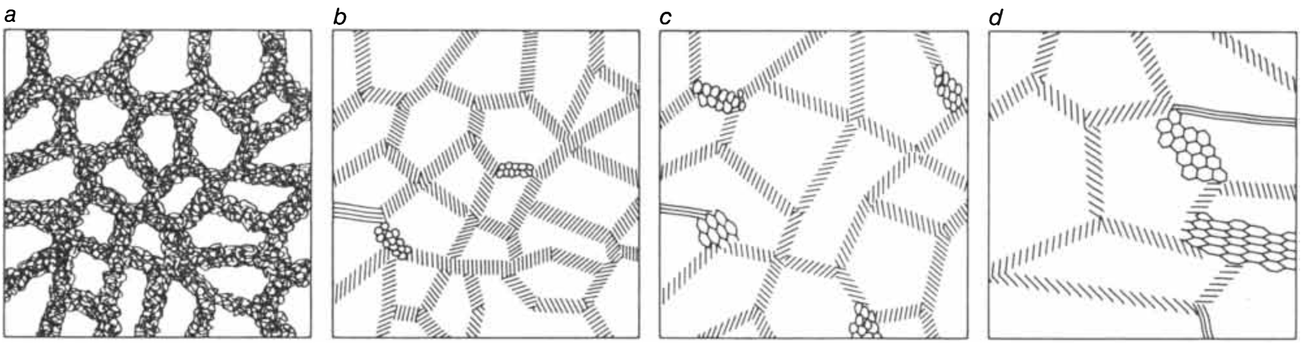
The dynamically recovered structure is quite stable. It can be retained if the hot-worked metal is cooled fairly quickly to room temperature. If the metal is held at the working temperature, recrystallization does occur; in aluminum, for example, it will occur within half an hour at 400 degrees Celsius.

The dynamically recovered structure is considerably stronger than the recrystallized structure. Extruded forms of unrecrystallized aluminum-magnesium alloy have enhanced strength for architectural purposes. Certain aluminum alloys can be heat-treated to greater strength if the subgrain structure is retained.

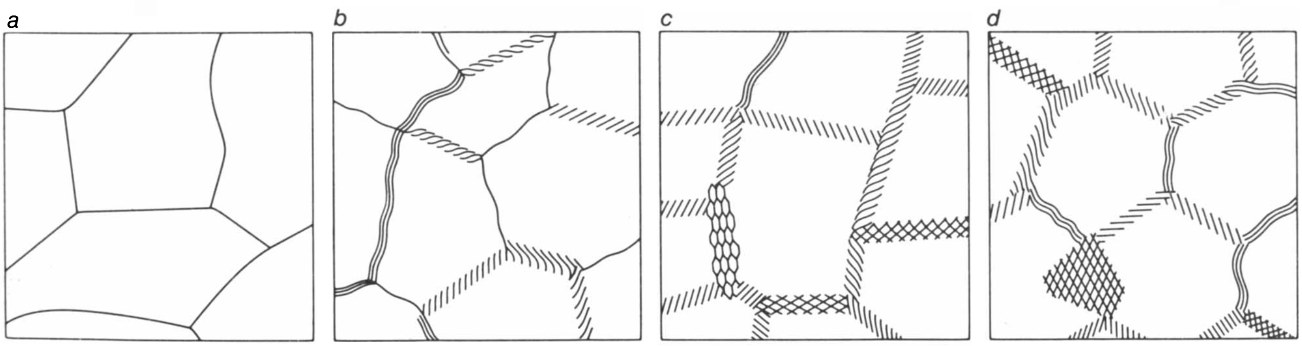
Metals such as copper, nickel and austenitic iron, in which dislocations have difficulty leaving the slip planes,




**CHANGE IN SUBSTRUCTURE** during cold deformation of a metal is depicted. Before deformation the individual dislocations form a simple network (*a*). At a light strain large cells are formed (*b*). At somewhat more strain the cells reach their smallest size (*c*). At further strain and thus further deformation (*d*) cell walls become much thicker. The metal's substructure develops as strain increases.



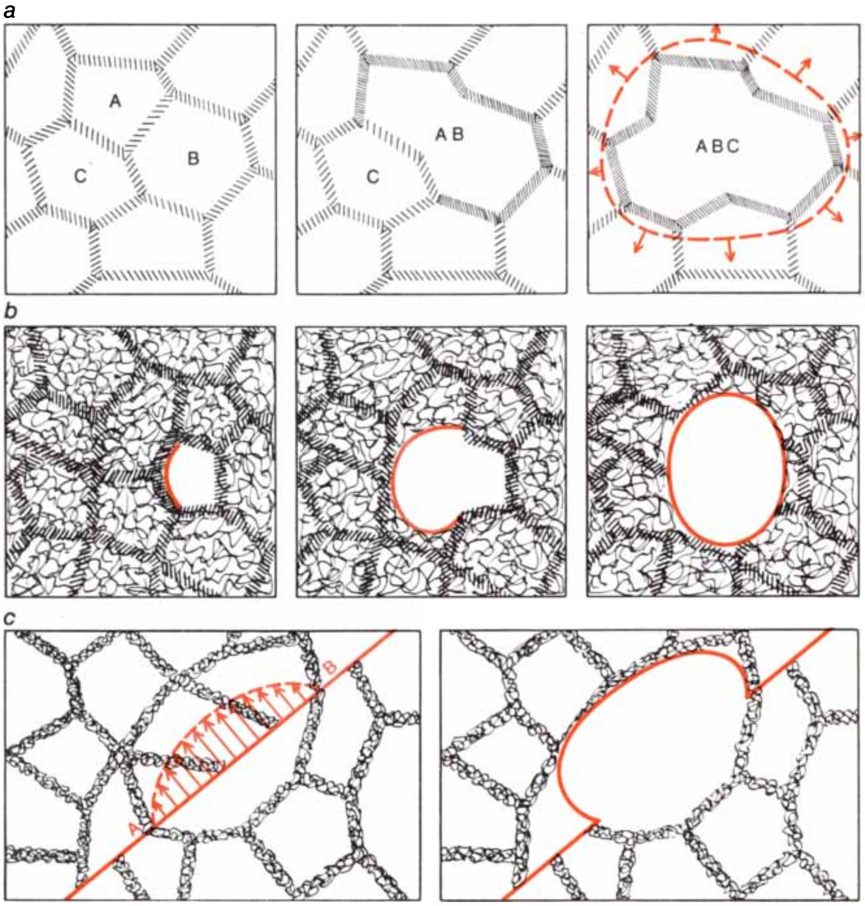

**RECOVERY DURING ANNEALING** begins with the cells in the thick-walled structure they attained during cold deformation (*a*). After brief annealing many dislocations annihilate one another, so that the sub-boundaries become thinner (*b*). With further annealing the cells continue to grow (*c*). Eventually the subgrains enlarge (*d*). Annealing a metal that has been worked restores its ductility.




**EFFECT OF HOT-WORKING** on the substructure of a metal is portrayed, starting with the structure before deformation (*a*) and progressing through stages of increasing strain (*b—d*). The subgrains are much larger and the sub-boundaries are more regular than they are in the substructure resulting from the deformation of a metal by cold-working. Creep gives similar but larger subgrains.

behave somewhat like these aluminum alloys at strains of up to .5 (a 40 percent reduction) at a strain rate of .1 per second (meaning that each meter of length increases .1 meter per second) or at strains of about 2.3 (90 percent reduction) at a strain rate of 100 per second. These limits are greater than the deformations usually found in forging or rolling but are not greater than those found in extrusion. For equivalent conditions of temperature and strain rate the subgrains become smaller and their walls become thicker and denser, with a decrease in the ability of dislocations to cross-glide and climb to achieve annihilation.

When working is stopped, the high density of dislocations causes these materials to recrystallize quite rapidly. Copper, for example, needs only two seconds at 600 degrees C. This form of recrystallization is termed static, since it occurs after deformation is completed. Therefore it is not usually possible under industrial conditions to preserve the structure attained during working. The recrystallization is advantageous, however, if the material is going to be subjected to a further stage of hot-working, such as another blow of a forging hammer or another pass in a hot-strip mill. The intermediate recrystallization decreases the flow stress and increases the ductility. Static recrystallization also leaves the metal soft and ductile for cold-forming operations.




**NUCLEUS FOR RECRYSTALLIZATION can form in several ways. As a result of recovery (*a*) the dislocations between cells *A* and *B* are attracted to surrounding sub-boundaries, where some of the dislocations annihilate one another but most of them enter a sub-boundary, increasing the degree of misorientation. With further recovery *A*, *B* and *C* coalesce into one crystallite surrounded by a boundary of high misorientation. When the boundary migrates, *ABC* is a nucleus for recrystallization. In a metal where deformation creates a high density of dislocations in a small region (*b*) the dislocations combine at the beginning of annealing into a boundary of high misorientation. As portrayed in the succeeding panels, the boundary migrates and becomes a nucleus for recrystallization. Such a nucleus can also be formed when an original boundary bulges out (*c*). Bulging usually occurs when there is a large cell on one side of a grain boundary (*colored line*), with its walls anchored as shown at *A* and *B*, and when the density of dislocations is higher on the other side of the boundary.**

One also finds dynamic recrystallization in certain metals. This phenomenon, which occurs while deformation is going on, is observed in planar-array metals being deformed to high strains, such as in extrusion. The phenomenon was discovered about 15 years ago by Claude Rossard and P. Blain in France and by D. Hardwick, C. Michael Sellars and one of us (Tegart) in Britain.

This dynamic recrystallization is nucleated when grain boundaries form from the dense tangles of dislocations that build up because cross-glide and climb are limited and do not bring about sufficient annihilation. As in static recrystallization, the grain boundary migrates into the deformed metal, leaving behind a new crystal almost devoid of dislocations. Continuing deformation, however, causes a dislocation substructure to form within the nucleus. With increasing strain other nuclei form here and there in the material that has not yet recrystallized. With still further strain the regions that recrystallized first become deformed enough for nuclei to form again.

Thus as straining is continued nuclei will continually be forming at random. As a result they will be equally distributed throughout the material. Since the recrystallized material is not as strong as the worked material, the average flow stress will be lower than the peak just before recrystallization.

Dynamic recrystallization also plays an important role in imparting high ductility to hot metal. The repeated migration of boundaries during recrystallization prevents the formation of cracks at grain boundaries. The formation of such cracks is the common mode of fracture at high temperature.

When deformation is stopped, the nuclei that have just formed continue to grow, leading to rapid static recrystallization. The grains resulting from this static recrystallization are larger than the average grain resulting from dynamic recrystallization because the nuclei that would be produced by a further increment of strain do not form. In both cases, however, the dependence of grain size on temperature and strain rate is similar.

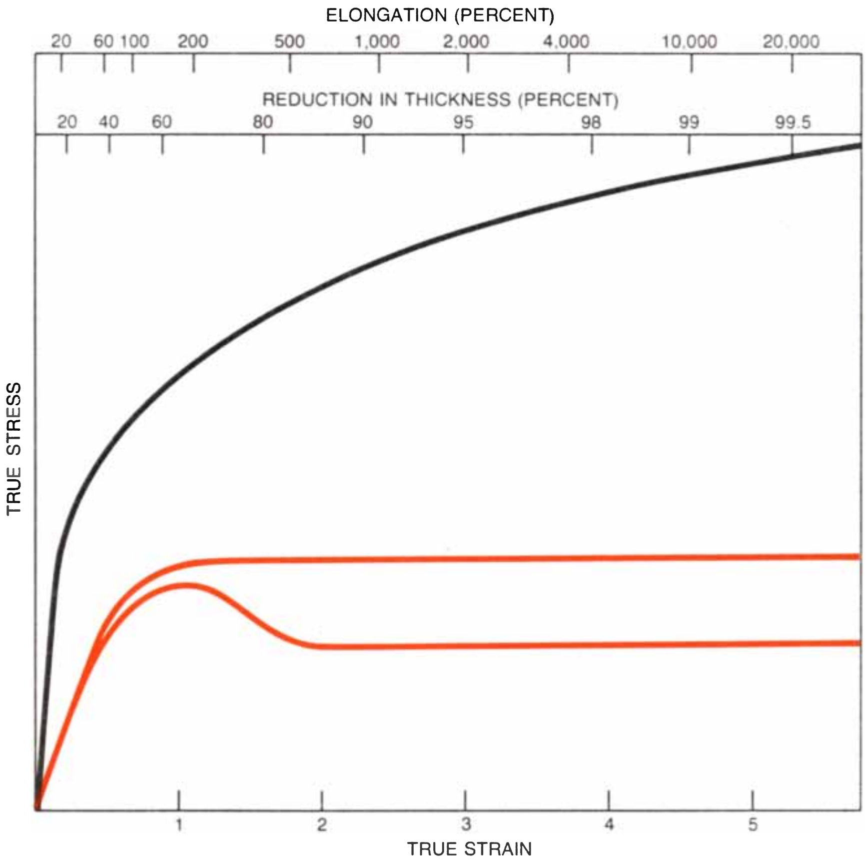
Until recently the findings we have described were not much applied in industry. The metallurgical engineer was content to rely on empirical principles that had served adequately for a long time in managing hot-working processes to economically produce shapes with acceptable surface conditions, dimensional tolerances and mechanical properties. In the face of increasing competition during the past decade, however, interest has mounted in applying the new findings to control hot-working processes so as to achieve microstructures that make the product much stronger and considerably less brittle.

A major recent commercial development has been the production of structural steels with a strength of from 60,000 to 85,000 pounds per square inch, compared with about 20,000 pounds per square inch for standard structural steels. The attractive properties of such "controlled-rolled" steels have led to a concentration of research in this field by steel companies throughout the world. Two areas have received the most attention because of the large tonnages involved: the production of thick plates for pipelines and bridges and of thin strip for vehicles and structures.

The most important microstructural variable is grain size, since a fine grain size leads to increased strength combined with decreased brittleness. Grain refinement depends on control of recrystallization and thus on control of the forming schedule. In rolling and forging, which constitute the major industrial hot-working procedures, metals are deformed by increments of strain, and the times between deformations are as important as the deformations themselves, since the length of the intervals determines the extent to which static recrystallization can occur. The amount of strain at each deformation ranges from .1 to .35 (reductions of from 10 to 30 percent), and the delay between successive deformations ranges from one second to two minutes.

The rate of static recrystallization is markedly dependent on temperature. At the normal hot-working temperature for steel (about 1,000 degrees C.) recrystallization is sufficiently rapid to be essentially complete between successive deformations. Moreover, delay at such a temperature leads to coarse grains and poor properties. Unfortunately processing at lower temperatures, where recrystallization is slower and finer grains can be obtained, means that the metal has lower ductility and that the machine has to apply greater force. The addition of a small amount of niobium markedly retards recrystallization in low-carbon steel, thereby leading to better control of the final grain size at hot-working temperatures.

Although these "thermomechanical"




**INCREASE IN STRENGTH** of metal is charted for cold-working (*black*) and hot-working (*color*). Strength increases with stress. The upper curve relating to hot-working reflects dynamic recovery, a dislocation-softening mechanism that limits the increase in strength. The lower curve reflects dynamic recrystallization, wherein soft grains replace distorted grains.

treatments have been applied mainly to low-carbon steels, such treatments can also be used with certain alloy steels in a variety of ways to give increased strength and toughness. The treatment that has attracted the most attention is ausforming, in which steel in the austenitic condition is warm-worked to produce a dense structure of dislocations that is retained during the transformation of the steel to martensite. (Austenite, martensite, pearlite and bainite are names for particular microstructures that steel attains spontaneously during hot-working; the microstructures are a consequence of carbon content, temperature and the time sequence of processing.) The temperatures involved in ausforming (from 450 to 650 degrees C.) are below the normal hot-working range, so that the loads on the equipment are high. As a result the application of the process has been limited to small sections of steel, but in them it brings about great strength (250,000 to 350,000 pounds per square inch).

Isoforming is another process that has received considerable attention. Deformation is applied during the isothermal transformation of steel to pearlite at temperatures of from 550 to 750 degrees C. The result is a fine-grained material with a strength of about 100,000 pounds per square inch. Although the emphasis in thermomechanical treatment has been on steel, the same possibility for raising strength by controlling structure exists with nonferrous metals. Thermomechanical treatments have been applied successfully to alloys based on aluminum, copper, titanium and nickel.

An important aspect of this technology is its bearing on mineral supplies and the consumption of energy. Since the products made in this manner are lighter than products of comparable strength made by conventional methods, they require less in the way of raw material. Compared with cold-working, hot deformation reduces the energy required to build and operate the forming machines and annealing furnaces.

The work we have described also has a bearing on the reduction of creep, which will increasingly become a problem as more electric power is produced by nuclear reactors. For example, the pressure tubes in Canadian reactors are made of zirconium alloy extruded at high temperature. The lifetime of these tubes is limited by creep. A similar problem can be foreseen in breeder and fusion reactors. Much research is therefore being devoted to producing creep-resistant alloys that can still be extruded.

# MATHEMATICAL GAMES

## *Six sensational discoveries that somehow or another have escaped public attention*

by Martin Gardner

Has the steady rise of public interest in occultism and pseudoscience over the past 10 years in the U.S. been something apart from public understanding of scientific knowledge? The two have interacted more strongly than most people realize. Important advances in science have been crowded out of newspapers, magazines, radio and television to make room for reports on poltergeists, demon possession, psychic healing, prehistoric visits to the earth by astronauts from other worlds, the vanishing of ships and planes in the Bermuda Triangle, the emotional life of plants, the primal scream and so on ad nauseam.

The effect is intensified by an increasing backlog of articles submitted to scientific journals. It is not unusual for several years to elapse between the acceptance of a scientific paper and its publication. In the meantime the author of an unpublished article about an important new discovery may keep his results secret for fear that a rival colleague might steal them and publish first.

As a public service I shall comment briefly on six major discoveries of 1974 that for one reason or another were inadequately reported to both the scientific community and the public at large. The most sensational of last year's discoveries in pure mathematics was surely the finding of a counterexample to the notorious four-color-map conjecture. That theorem, as all readers of this department must know, is that four colors are both necessary and sufficient for coloring all planar maps so that no two regions with a common boundary are the same color. It is easy to construct maps that require only four colors, and topologists long ago proved that five colors are enough to color any map. Closing the gap, however, had eluded the greatest minds in mathematics. Most mathematicians have believed that the four-color theorem is true and that eventually it would be established. A few suggested it might be Gödel-undecidable. H. S. M. Coxeter, a geometer at the University of Toronto, stood almost alone in believing that the conjecture is false.

Coxeter's insight has now been vindicated. Last November, William McGregor, a graph theorist of Wappingers Falls, N.Y., constructed a map of 110 regions that cannot be colored with fewer than five colors [*see upper illustration on page 128*]. McGregor's technical report will appear in 1978 in the *Journal of Combinatorial Theory,* Series B.

In number theory the most exciting discovery of the past year is that when the transcendental number $e$ is raised to the power of $\pi$ times $\sqrt{163}$, the result is an integer. The Indian mathematician Srinivasa Ramanujan had conjectured that $e$ to the power of $\pi\sqrt{163}$ is integral in a note in the *Quarterly Journal of Pure and Applied Mathematics* (Volume 45, 1913–14, page 350). Working by hand, he found the value to be 262,537,412,640,768,743.999,999,999,999,.... The calculations were tedious, and he was unable to verify the next decimal digit. Modern computers extended the 9's much farther; indeed, a French program of 1972 went as far as two million 9's. Unfortunately no one was able to prove that the sequence of 9's continues forever (which, of course, would make the number integral) or whether the number is irrational or an integral fraction.

In May, 1974, John Brillo of the University of Arizona found an ingenious way of applying Euler's constant to the calculation and managed to prove that the number exactly equals 262,537,412,640,768,744. How the prime number 163 manages to convert the expression to an integer is not yet fully understood. Brillo's proof is scheduled to appear in a few years in *Mathematics of Computation.*

There were rumors late in 1974 that $\pi$ would soon be calculated to six million decimal places. This may seen impressive to laymen, but it is a mere computer hiccup compared with the achievement of a special-purpose chess-playing computer built in 1973 by the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology. Richard Pinkleaf, who designed the computer with the help of ex-world-chess-champion Mikhail Botvinnik of the U.S.S.R., calls his machine MacHic because it so often plays as if it were intoxicated.

Unlike most chess-playing programs, MacHic is a learning machine that profits from mistakes, keeping a record of all games in its memory and thus steadily improving. Early in 1974 Pinkleaf started MacHic playing against itself, taking both sides and completing a game on an average of every 1.5 seconds. The machine ran steadily for about seven months.

At the end of the run MacHic announced an extraordinary result. It had established, with a high degree of probability, that pawn to king's rook 4 is a win for White. This was quite unexpected because such an opening move has traditionally been regarded as poor. MacHic could not, of course, make an exhaustive analysis of all possible replies. In constructing a "game tree" for the opening, however, MacHic extended every branch of the tree to a position that any chess master would unhesitatingly judge to be so hopeless for Black that Black should at once resign.

Pinkleaf has been under enormous pressure from world chess leaders to destroy MacHic and suppress all records of its analysis. The Russians are particularly concerned. I am told by one reliable source that a meeting between Kissinger and Brezhnev will take place in June, at which the impact on world chess of MacHic's discovery will be discussed.

Bobby Fischer reportedly said that he had developed an impregnable defense against P-KR4 at the age of 11. He has offered to play it against MacHic provided that arrangements can be made for the computer to play silently and provided that he (Fischer) is guaranteed a win-or-lose payment of $25 million.

The reaction of chess grand masters to MacHic's discovery was mild compared with the shock waves generated among leading physicists by last year's discovery that the special theory of relativity contains a logical flaw. The crucial "thought experiment" is easily described. Imagine a meter stick traveling through space like a rocket, on a straight line colinear with the stick. A plate with a circular hole one meter in diameter is parallel to the stick's path and moving perpendicularly to it [*see lower illustration on page 128*]. We idealize the experiment by assuming that both the plate and the meter stick have zero thickness. The two objects are on a precise collision course. At the same instant the center of the meter stick and the center of the hole will coincide.

Assume that the plate is the fixed inertial frame of reference and the meter stick is moving so fast that it is Lorentz-contracted by a factor of 10. In this inertial frame the stick has a length of 10 centimeters. As a result it will pass easily through the hole in the rapidly rising plate. (The speed of the rising plate is immaterial.)

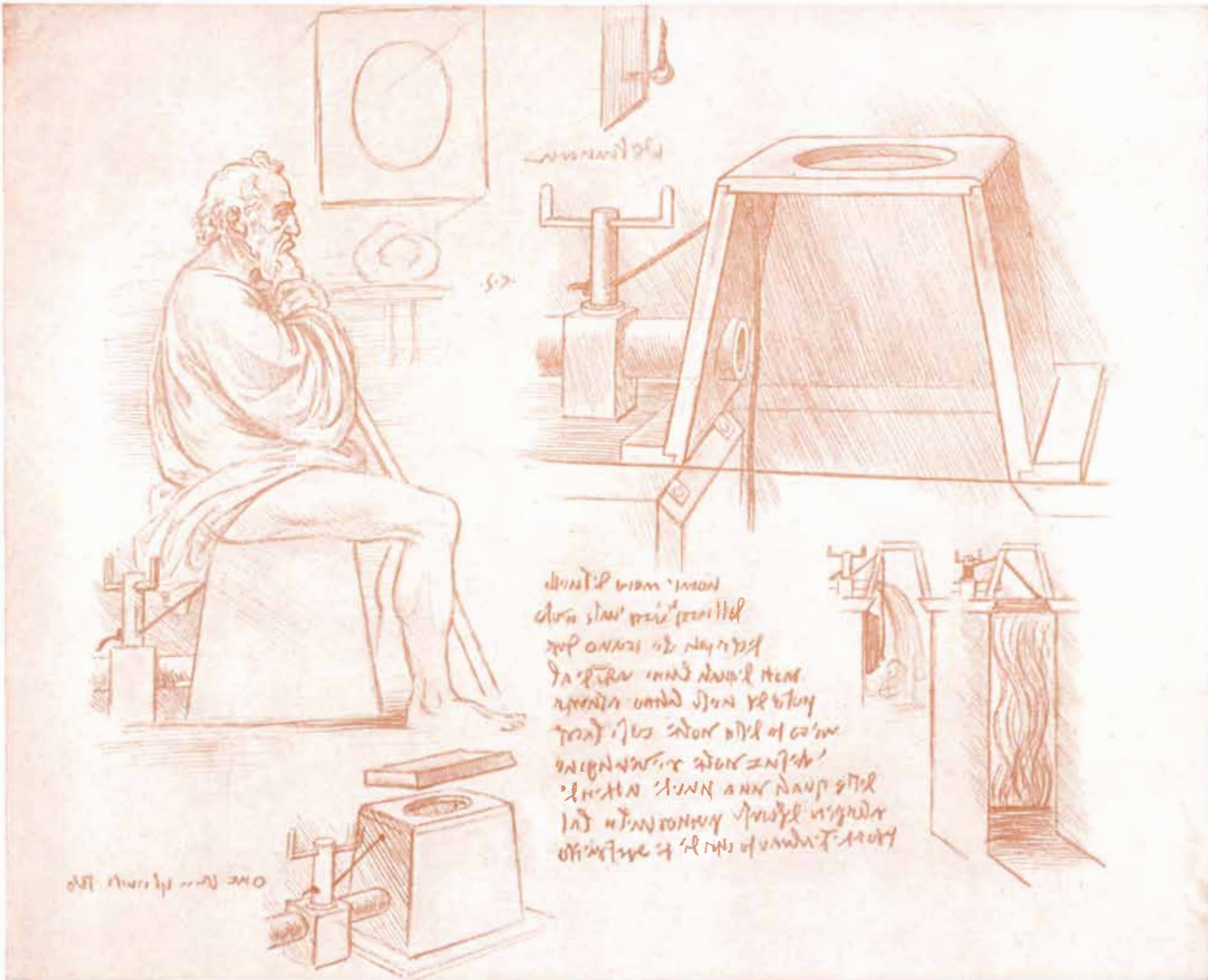
Now consider the situation from the standpoint of the meter stick's inertial frame. The plate is moving in the opposite horizontal direction, and so now it is the hole that is Lorentz-contracted to 10 centimeters. There is no way the 10-centimeter hole can move up past the meter stick without a collision. The two situations are not equivalent, and thus a fundamental assumption of special relativity is violated.

Physicists have long realized that the general theory of relativity is weakly confirmed, but the special theory had been confirmed in so many ways that its sudden collapse came as a great surprise. Humbert Pringle, the British physicist who discovered the fatal *Gedankenexperiment,* reported it in a short note last summer in *Reviews of Modern Physics,* but the full impact of all of this has not yet reached the general public.

When facsimiles of two lost notebooks of Leonardo da Vinci's were published last fall by McGraw-Hill, they were widely reviewed. The public learned of many hitherto unknown inventions made by Leonardo: a system of ball bearings surrounding a conical pivot (thought to have been first devised by Sperry Gyroscope in the 1920's), a worm screw credited to an 18th-century clockmaker and dozens of other devices, including a bicycle with a chain drive.

In view of the publicity given the McGraw-Hill volumes it is hard to understand why the media failed to report last December on the discovery of a drawing that had been missing from the first notebook. This notebook, known as *Codex Madrid I* (it had been found 10 years earlier in the National Library in Madrid), is a systematic treatise of 382 pages on theoretical and applied mechanics [see "Leonardo on Bearings and Gears," by Ladislao Reti; SCIENTIFIC AMERICAN, February, 1971]. There had been much speculation on the nature of the missing page. Augusto Macaroni of the Catholic University of Milan observed that the sketch was in a section on hydraulic devices, and he speculated that it dealt with some type of flushing mechanism.

The missing page was found shortly before Christmas by Ramón Paz y Bicuspid, head of the manuscript division of the Madrid Library. It was Bicuspid who had originally found the two lost notebooks. The missing page had been torn from the manuscript and inserted in a 15th-century treatise on the Renaissance art of perfume making. The illustration below reproduces a photocopy of



*Leonardo invents the valve flush toilet* the original drawing. As the reader can see at once, Professor Macaroni was on target. The drawing establishes Leonardo as the first inventor of the valve flush toilet.

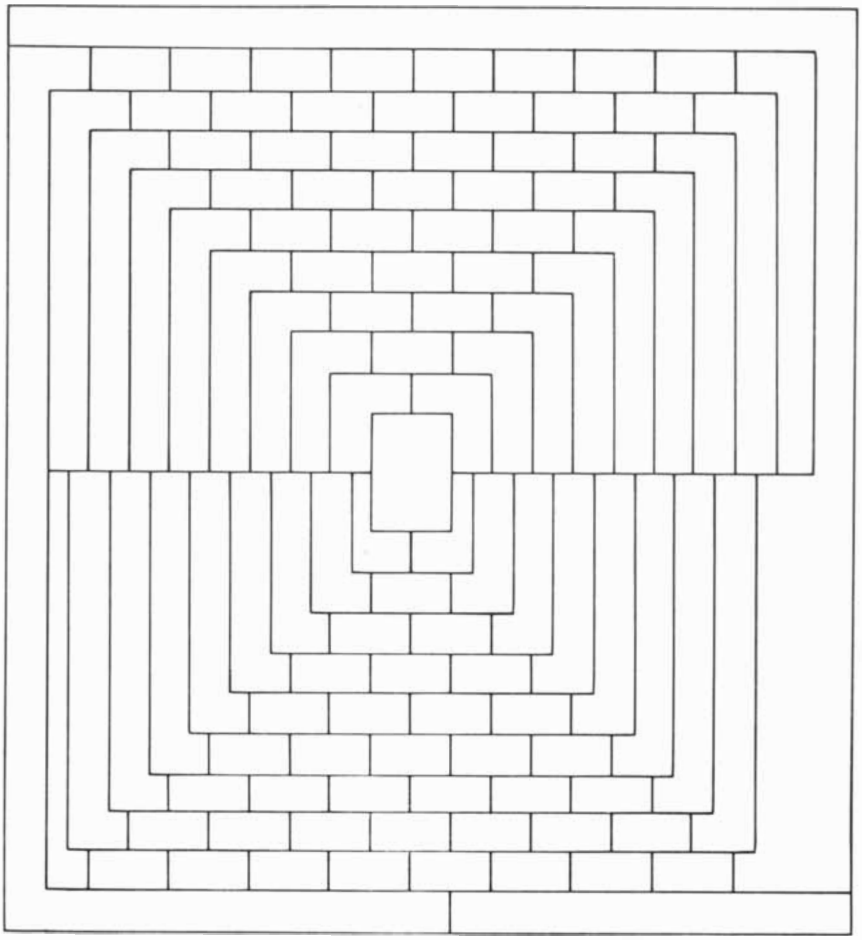
It had long been known that Leonardo had invented a folding toilet seat and had proposed a water closet with continuously running water in channels inside walls, a ventilating shaft to the roof and suspended weights to make sure the entrance door closed. Until now, however, the first valve flush toilet has always been credited to Sir John Harington, a godson of Queen Elizabeth. Harington described it amusingly in his book *The Metamorphosis of Ajax,* 1596, a cloacal satire that got him banished from the court. Although his "Ajax" actually was built at Kelston near Bath, it was not until 200 years later that it came into general use.

The first English patent for a valve flush toilet was granted in 1775 to Alexander Cummings, a watchmaker. Modern mechanisms, in which a ball float and automatic cutoff stopper limit the amount of water released with each flush, date from the early 19th-century patents of Thomas Crapper, a British manufacturer of plumbing fixtures who died in 1910. (See *Clean and Decent: The Fascinating History of the Bathroom and Water Closet,* by Lawrence Wright, Routledge and Kegan Paul, 1960, and *Flushed with Pride: The Story of Thomas Crapper,* by Wallace Reyburn, Prentice-Hall, 1971.)

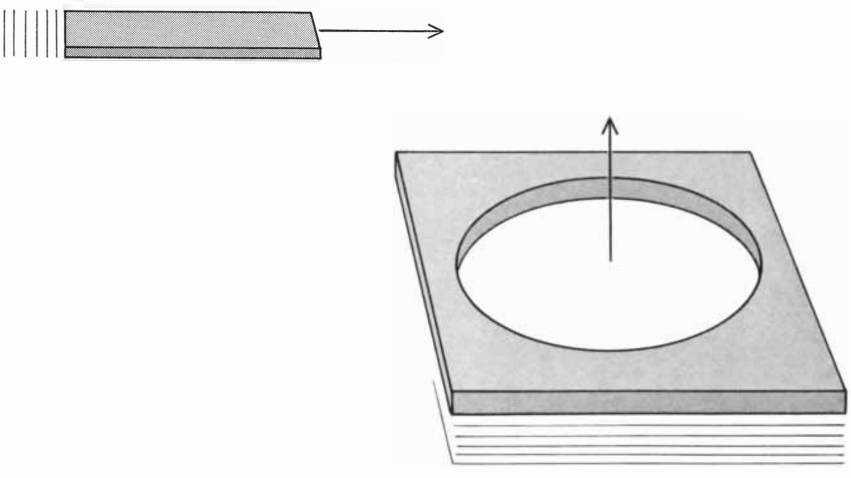
Although hundreds of books on parapsychology spewed forth from reputable publishing houses in 1974, not one reported the most sensational psi discovery of the century: a simple motor that runs on psi energy. It was constructed in 1973 by Robert Ripoff, the noted Prague parapsychologist and founder of the International Institute for the Investigation of Mammalian Auras. When Henrietta Birdbrain, an American expert on Kirlian photography, visited Prague early last year, Dr. Ripoff taught her how to make his psychic motor. Ms. Birdbrain demonstrated the device many times in her lectures, but as far as I am aware the only published report on it appeared in the Boston monthly newspaper *East West Journal,* May, 1974, page 21.

Readers are urged to construct and test a model of the motor. The first step is to cut a three-by-seven-inch rectangle from a good grade of bond paper. Make a tiny slot in the paper at the spot shown [*see illustration on opposite page*]. The slot must be 3/8 inch long and exactly in the center of the strip, 1/8 inch from the top edge. Bend the paper into a cylinder, overlapping the ends 5/16 inch, and glue the ends together. Cut a second slot in the center of the overlap, directly opposite the preceding one. It must be the same size and the same distance from the top.

From a file card or a piece of pasteboard of similar weight cut a strip 3/8 inch by three inches. Insert a fine, sharp-pointed needle twice through the center of the strip as shown in step 3. The point of the needle should be no more than 1/4 inch below the bottom edge of the strip. Push the ends of the strip through the cylinder's two slots, as shown in step 4, taking care not to bend the strip. The final step is to balance the needle on top of a narrow bottle at least



*The four-color-map theorem is exploded*



*A thought experiment that disproves special relativity* four inches high (step 5). It is essential that the top of the bottle be either glass (preferable) or very hard smooth plastic.

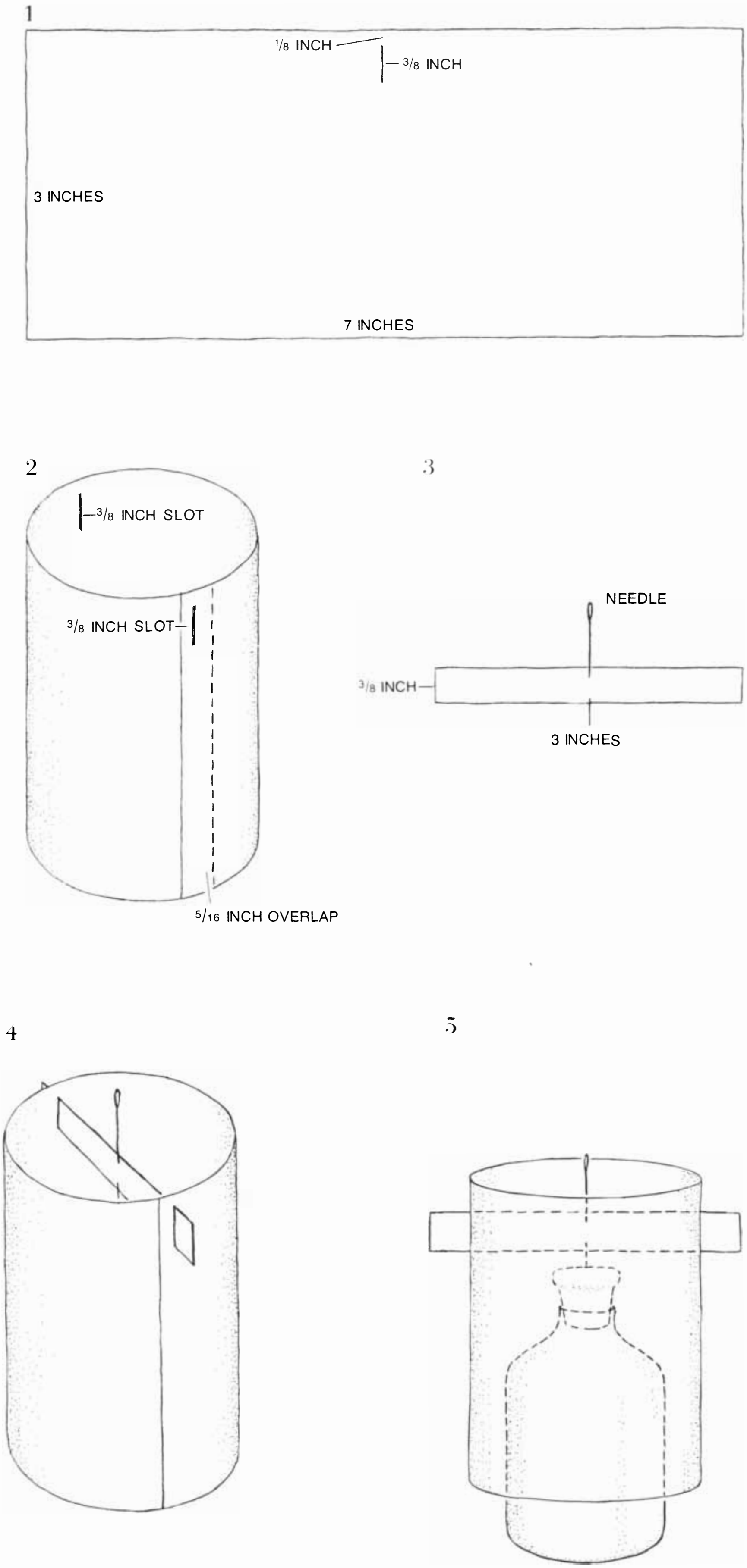
Adjust the strip in the slots until the cylinder hangs perfectly straight, its side the same distance from the bottle all around. With scissors snip the ends of the strip so that each end projects 1/4 inch on each side.

Place the little motor on a copy of the Bible or the *I Ching*, with the book's spine running due north and south. Sit in front of the motor, facing north. Hold either hand, cupped as shown in the illustration on the next page, as close to the cylinder as you can without actually touching it. You must be in a quiet room, where the air is still. Make your mind blanker than usual and focus your mental energy on the motor. Strongly will it to rotate either clockwise or counterclockwise. Be patient. It is normally at least one full minute before the psi energy from your aura takes effect. When it does, the cylinder will start to rotate slowly.

Some people, of course, have a stronger psi field than others. A lot depends on your mental state. At times the motor refuses to turn. At other times it begins to turn almost as soon as you start concentrating. Experiments show that for most people it is easier to make the motor rotate counterclockwise with psi energy from your right hand and clockwise with the energy from your left. At times negative psi takes over and the motor turns in the direction opposite to the direction being willed. As Dr. Rhine has taught us, psi effects are elusive, skittish and unpredictable.

The motor is currently under extensive investigation at numerous parapsychology laboratories around the world. Russian experts are convinced the energy that turns the motor is the same as the psychokinetic energy that enables the Israeli psychic Uri Geller to bend silverware, the Russian "sensitive" Ninel Kulagina to levitate table-tennis balls and the Brooklyn psychic Dean Kraft to make pieces of candy leap out of bowls and pens crawl across rugs. When Kulagina holds both hands near the motor, the cylinder flies straight up in the air for several meters. A book on the Ripoff rotor (as it is called in Prague), with papers by 12 of the world's leading parapsychologists, is being edited by Ms. Birdbrain and will be published later this year by Putnam.

James Randi, the magician, contends that by using trickery he can make the motor spin rapidly in either direction. Of course, that does not explain why the motor operates so efficiently for thou-




*A psychic motor is made*

sands of people who know nothing about conjuring.

I should welcome the opinion of *Scientific American* readers on what causes the Ripoff rotor to rotate. I cannot reply to the letters individually, but I shall report here on them later.

Answers to the assortment of problems presented in this department last month follow:

1. Regardless of the parameters (the initial length of the rubber rope, the worm's speed and how much the rope stretches after each unit of time), the worm will reach the end of the rope in a finite time. This is also true if the stretching is a continuous process, at a steady rate, but the problem is easier to analyze if the stretching is done in discrete steps.

One is tempted to think one can see that the worm will make it. Since the rope expands uniformly, like a rubber band, the expansion is like looking at the rope through increasingly strong magnifying lenses. Because the worm is always making progress, must it not eventually reach the end? Not necessarily. One can progress steadily toward a goal forever without ever reaching it. The worm's progress is measured by a series of decreasing fractions of the rope's length. The series could be infinite and yet converge at a point far short of the end of the rope. Indeed, such is the case if the rope stretches by doubling its length after each second.

The worm, however, does make it. There are 100,000 centimeters in a kilometer, so that at the end of the first second the worm has traveled 1/100,000th of the rope's length. During the next second the worm travels (from its previous spot after the stretching) a distance of 1/200,000th of the rope's length after the rope has stretched to two kilometers. During the third second it covers 1/300,000th of the rope (now three kilometers) and so on. The worm's progress, expressed as fractional parts of the entire rope, is

$$\frac{1}{100{,}000}\left(1+\tfrac{1}{2}+\tfrac{1}{3}+\tfrac{1}{4}+\dots+\tfrac{1}{n}\right).$$

The series inside parentheses is the familiar harmonic one that diverges and therefore can have a sum as large as we please. The partial sum of the harmonic series is never an integer. As soon as it exceeds 100,000, however, the above expression will exceed 1, which means that the worm has reached the end of the rope. The number of terms, $n$, in this partial harmonic series will be the number of seconds that have elapsed. Since the worm moves one centimeter per second, $n$ is also the final length of the rope in centimeters.

This enormous number, correct to within one minute, is

$$e^{100{,}000-\gamma}\pm 1,$$

where $\gamma$ is Euler's constant. It gives a length of rope that vastly exceeds the diameter of the known universe and a time that vastly exceeds present estimates of the age of the universe. For a derivation of the formula see "Partial Sums of the Harmonic Series," by R. P. Boas, Jr., and J. W. Wrench, Jr., *American Mathematics Monthly*, Volume 78, October, 1971, pages 864–870.

2. As David M. Keller disclosed in his article "The Sigil of Scoteia" (*Kalki*, Volume 2, No. 2, 1968), one simply turns the Sigil upside down. "Additional difficulties are found in the division of words at the ends of lines," Keller writes, "and in the substitution of odd characters for some of the letters." The Sigil reads:

"James Branch Cabell made this book so that he who will may read the story of mans eternally unsatisfied hunger in search of beauty. Ettarre stays inaccessible always and her lovliness is his to look on only in his dreams. All men she must evade at the last and many are the ways of her elusion."

3. It is hard to believe, but the best strategy in the integer-choosing game is to limit one's choices of numbers to 1, 2, 3, 4 and 5. The selection is made at random, with the relative frequencies of 1/16 for numbers 1 and 5, 4/16 for number 3 and 5/16 for numbers 2 and 4. One could have in one's lap a spinner designed for picking numbers according to these frequencies.

For a proof of the strategy see "A Psychological Game," by N. S. Mendelsohn, *American Mathematical Monthly*, Volume 53, February, 1946, pages 86–88, and pages 212–215 of I. N. Herstein and I. Kaplansky's *Matters Mathematical* (Harper and Row, 1974).

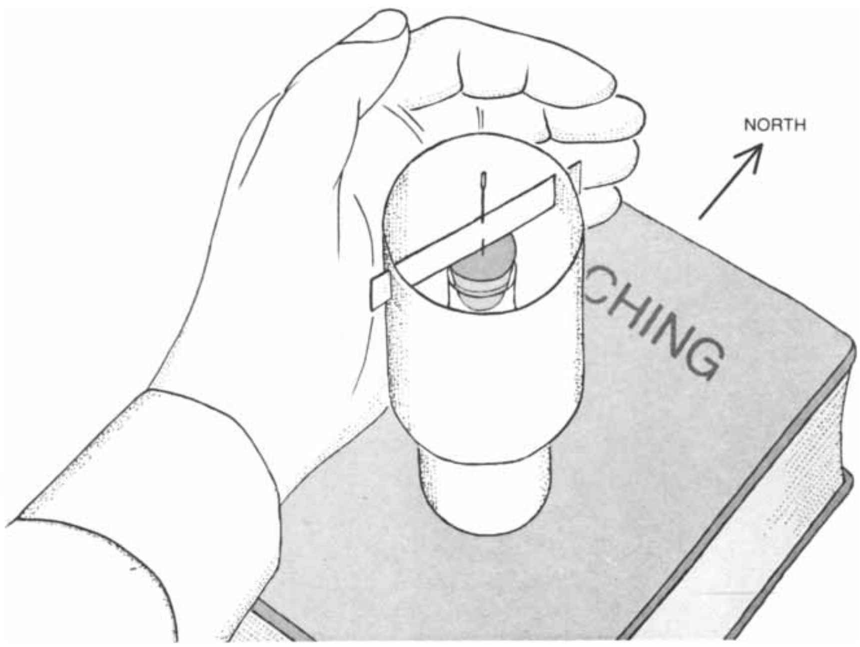
4. John Edson Sweet's solution to the three-circle theorem is given in the answer to Problem 62 in L. A. Graham's *Ingenious Mathematical Problems and Methods* (Dover, 1959). Instead of circles, suppose you are looking down on three unequal spheres. The tangent lines for each pair of balls are the edges of three cones into which the two balls fit snugly. The cones rest on the plane that supports the balls and the apexes of the cones therefore lie on the plane.

Now imagine that a flat plate is placed on top of all three balls. Its underside is a second plane, tangent to all three balls and tangent to all three cones. This second plane also will contain the three apexes of the cones. Because the apexes lie on both planes, they must lie on the intersection of the two planes, which of course is a straight line.

5. The obliterated chess game is

| | |
|---|---|
| 1. P-KB3 | 1. P-K4 or K3 |
| 2. K-B2 | 2. Q-B3 |
| 3. K-KT.3 | 3. QxP |
| 4. K-R4 | 4. B-K2 (mate). |

6. D. R. Kaprekar's method of testing

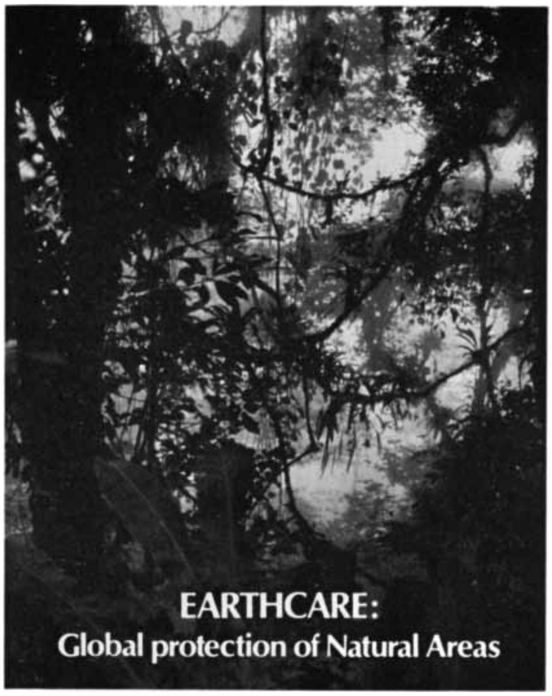



*How to apply psi energy to the psychic motor*

# WHAT IS THE EARTH COMING TO?

**Will whales survive? Why are deserts expanding in Africa and elsewhere? Is the ozone layer being eroded by aerosol sprays? What has the Earth's gene pool lost by destruction of tropical forests? How does land use regulation from the Alps to California's coast now protect natural areas from over-use? Can environmental impact analysis become a tool of every developer and government around the world?**

**Join diplomats, scientists and conservationists from around the world and register now for EARTHCARE, an innovative international conference on protection for the world's increasingly threatened natural areas. Organized by the Sierra Club and the National Audubon Society. 14th in the series of Biennial Wilderness Conferences. June 5-8, 1975, New York City.**




Join EARTHCARE participants in June and explore the problems and practical choices facing us in protecting the Earth's atmosphere, polar regions, oceans, rivers, wetlands, grasslands, urban open space. What unwitting damage does one country do to another? What are the economic, technological, and world consumer demands that are having increasingly drastic effects on these areas? What can citizens of each country do?

United Nations Secretary-General Kurt Waldheim will open the EARTHCARE Conference at the U.N. on June 5, World Environment Day. The EARTHCARE Declaration—a global conservation petition—will be opened for signature.

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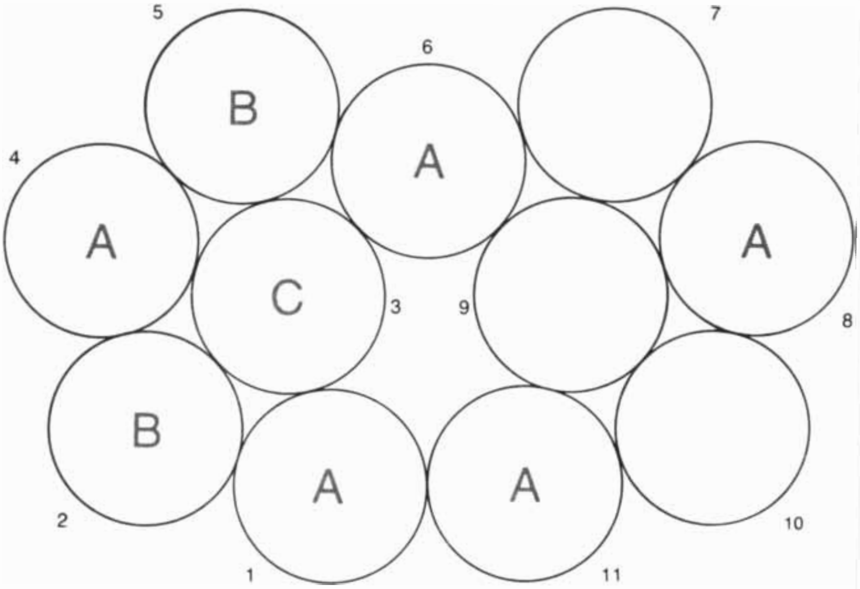



*Solution to last month's poker-chip problem*

a number, $N$, to see if it is a self-number is as follows. Obtain $N$'s digital root by adding its digits, then adding the digits of the result and so on until only one digit remains. If the digital root is odd, add 9 to it and divide by 2. If it is even, simply divide by 2. In either case call the result $C$.

Subtract $C$ from $N$. Check the remainder to see if it generates $N$. If it does not, subtract 9 from the last result and check again. Continue subtracting 9's, each time checking the result to see if it generates $N$. If this fails to produce a generator of $N$ in $k$ steps, where $k$ is the number of digits in $N$, then $N$ is a self-number.

For example, we want to test the year 1975. Its digital root, 4, is even, so that we divide 4 by 2 to obtain $C = 2$. 1975 minus 2 is 1973, which fails to generate 1975. 1973 minus 9 is 1964. This also fails. But 1964 minus 9 is 1955, and 1955 plus the sum of its digits, 20, is 1975; therefore 1975 is a generated number. Since 1975 has four digits, we would have had only one more step to go to settle the matter. With this simple procedure it does not take long to determine that the next self-year is 1985. There will be only one more self-year in this century: 1996.

7. It is easy to prove that the pattern of 11 circles [*see illustration above*] requires at least four colors to ensure that no pair of touching circles are the same color. Assume that it can be done with three colors. Label circles 1, 2 and 3 with colors $A$, $B$ and $C$ as shown. This determines the colors of 4, 5 and 6. We have a choice of two ways to color 7, but either way forces 11 to have the same color as 1, which it touches. Three colors are therefore not enough. It is almost certain that 11 is the minimal number of unit circles that form a pattern requiring four colors, although I know of no proof that a smaller number is impossible.

8. John Harris' 38-move solution to his rolling-cube puzzle is URDL, DRUL, LDRR, UULD, RUL; LDR, ULDD, RRUL, LDRU, LURD.

The letters stand for up, down, left and right. The solution is symmetrical, in the sense that the second half repeats the moves of the first half in reverse order except that down moves become up and vice versa. (See Harris' paper "Single Vacancy Rolling Cube Problems," *Journal of Recreational Mathematics*, Volume 7, Summer, 1974, pages 220–224. The journal is $10 per year to individual subscribers, $18 to institutions. It is published by Baywood Publishing Company, 43 Central Drive, Farmingdale, N.Y. 11735.)

Harris ends his article with a difficult problem that also involves eight cubes on an order-3 matrix. Color the cubes so that when they are on the matrix, with the center cell vacant, every exposed face is red and all hidden faces are uncolored. There will be just 24 red sides and 24 uncolored sides. The problem is to roll the cubes until they are back on the same eight cells, with the center cell vacant but with all the red sides hidden and the visible sides uncolored. Perhaps a reader can top Harris' solution of 84 moves.

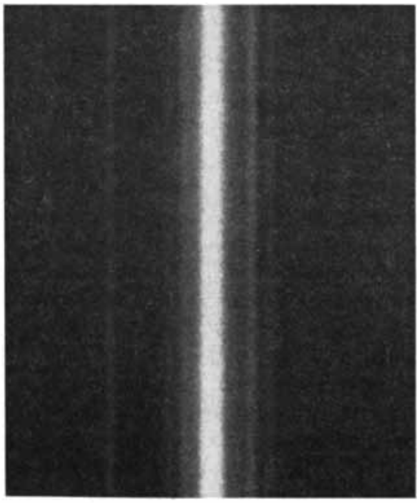
# THE AMATEUR SCIENTIST

## *An amateur undertakes the ultimate in mechanical precision, a ruling engine*

Conducted by C. L. Stong

Brian Manning, a British laboratory technician, has the distinction of being the first amateur to make a ruling engine that generates diffraction gratings of unsurpassed optical quality. A spectrograph fitted with one of the homemade gratings easily splits the green line of the mercury spectrum into its constituent pattern of finer lines. The spacing between one pair of the finer lines amounts to only .03 angstrom, about 120 trillionths of an inch.

The gratings consist of grids (two by three inches in size) of straight, uniformly spaced, parallel grooves ruled in the aluminum coating of flat glass mirrors. The precision required of the machine that makes the grooves is little short of awesome. The ruling engine must position a specially shaped diamond tool on the aluminum with enough pressure to displace the metal, push the diamond in a straight line to make the groove, lift it from the aluminum for the return stroke and simultaneously shift the aluminum sideways 66 millionths of an inch, plus or minus not more than half a millionth of an inch. Moreover, in ruling a grating the machine must repeat this operation precisely at least 45,000 times without stopping.



*Resolution of mercury line*

Manning, the persistent amateur who designed, constructed and debugged the engine, can be addressed in England at "Moonrakers," Stakenbridge, Churchill, near Kidderminster, Worcestershire. The project has absorbed most of his spare time for the past 21 years. A thick book could scarcely contain a full account of the construction details, but he summarizes the work as follows:

"My interest in diffraction gratings was aroused in 1954 by the desire for a grating to use in a spectroheliocope. I knew virtually nothing about diffraction gratings except that they were expensive and that a successful one had never been ruled by an amateur. The idea of making one with a ruling engine of my own construction was attractive. I had completed several reflecting telescopes in my home shop, which has a three-inch engine lathe and a drill press in addition to the conventional tools and materials for telescope making.

"I knew that ruling engines resemble the shaper, a common power tool in machine shops. The shaper has a reciprocating ram that carries a chisellike tool in a straight line. The chisel makes straight cuts in the workpiece during outbound strokes. The workpiece is displaced sideways automatically by its screw-driven carriage during each return stroke of the ram in preparation for the next cut.

"A well-maintained precision shaper can work to a tolerance of about .0001 inch. A ruling engine must work within .000001 inch! As the late Albert G. Ingalls of *Scientific American,* who popularized telescope making as a hobby, once wrote: 'On the scale of ultraprecision with which we must deal in a ruling engine we may regard the machine as made of rubber!' Ingalls pointed out that the screw in shifting the carriage can be elastically compressed as much as .00001 inch—10 times the error that can be tolerated by the grating it pushes. This is why pioneering developers of ruling engines spent much time eliminating friction of the stick-slip type. The framework and the other parts of the ruling engine are similarly flexible because no perfectly rigid material exists.

"More than 80 percent of all gratings employed in research have been ruled with engines of purely mechanical design. The uniform spacing of the rulings, and hence the optical quality of the grating, can be no better than the quality of the screw and its mountings. Like many amateurs I tried without success to make and mount a screw of the required accuracy. Finally I hit on the idea of achieving the desired precision by using optical measurements of carriage displacement to control the rotation of a crude screw [*see illustration on opposite page*]. A similar scheme had been undertaken seven years earlier by George R. Harrison and his colleagues at the Massachusetts Institute of Technology, but I did not learn of that work until my engine had been finished.

"As the first of several experiments to measure carriage displacement I set up a Michelson interferometer on a cast-iron plate. The movable mirror of the interferometer was temporarily mounted on the end of a screw-actuated carriage of the kind that serves as a milling attachment on engine lathes. The light source was a neon lamp.

"When the instrument was in proper adjustment, it displayed a pattern of alternately dark and light interference fringes in the form of concentric circles that expanded or contracted as the carriage moved forward or backward. One difficulty was that the interval between bright fringes varied with the position of the moving mirror. Moreover, the conversion of the movement of the circular fringes into electric pulses with a photomultiplier tube turned out to be difficult.

"In time I learned of the Twyman-Green modification of the interferometer. In this scheme Michelson's extended light source is replaced by monochromatic rays that diverge from an illuminated pinhole placed at the focal point of a simple lens [*see bottom illus-*

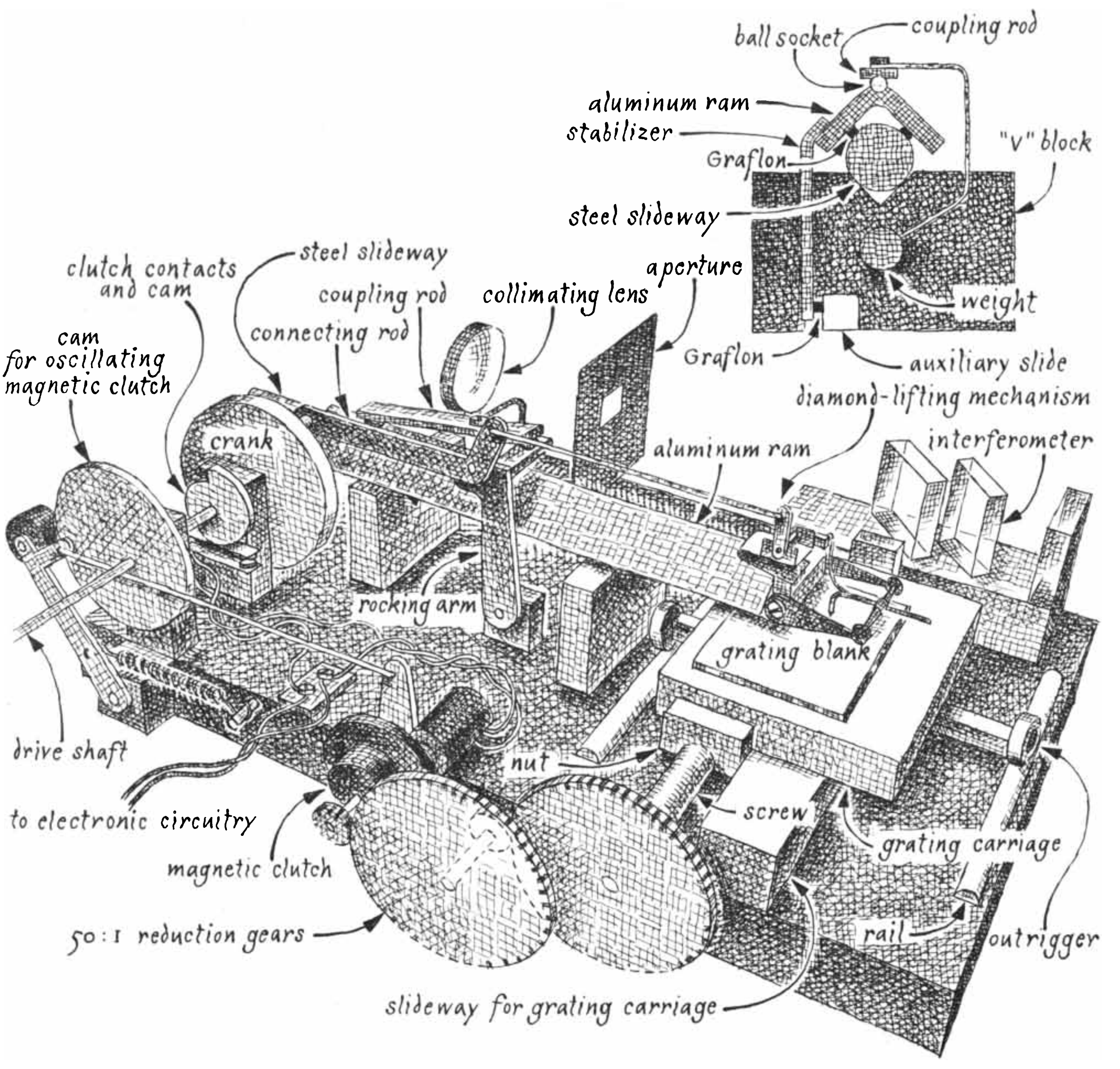
*tration on next page*]. The lens bends the diverging rays into a parallel bundle.

"By adjusting the mirrors to be virtually parallel the experimenter can produce a constant difference in the path of the interfering rays over the entire aperture of the interferometer. The pattern of concentric fringes is replaced by an illuminated field that varies sinusoidally from light to dark. The pulsating light falls on a photomultiplier tube. The electrical output of the tube is correspondingly sinusoidal, and the pulses vary in proportion to the displacement of the mirror.

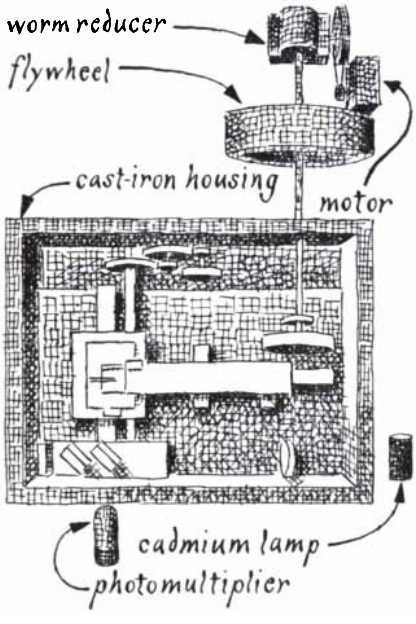
"Generating the interference effect throughout a three-inch excursion of the movable mirror requires that the interferometer be illuminated with light of a single color. The efficiency of the lamp must also be as high as possible to minimize heat that would expand the engine and ruin the grating. The only adequate sources of monochromatic light prior to the advent of the stabilized gas laser were gas-discharge lamps, particularly those filled with argon and mercury vapor. They were expensive. For some years a relatively inexpensive krypton lamp was available, but its brightness was barely adequate.

"In the end I built a cadmium lamp. To avoid the difficulty of sealing electrodes in glass I excited the lamp with radio-frequency energy. My first lamp operated for about 10 minutes before turning black. After much experimenting I hit on the right combination of temperature, filling pressure and glass.

"Most recently I have made the lamps with an electromagnetically enriched isotope of cadmium (Cd-114) that I get from the atomic energy establishment at Harwell in England. The light emission of this material is largely free of the fine spectral structure that broadens the blue emission line at 4,799.92 angstroms when ordinary cadmium is used. This




*Brian Manning's ruling engine*




*Plan view of the engine*

line matches the spectral response of my Type 931A photomultiplier. The improved lamps have a minimum operating life of 1,000 hours.

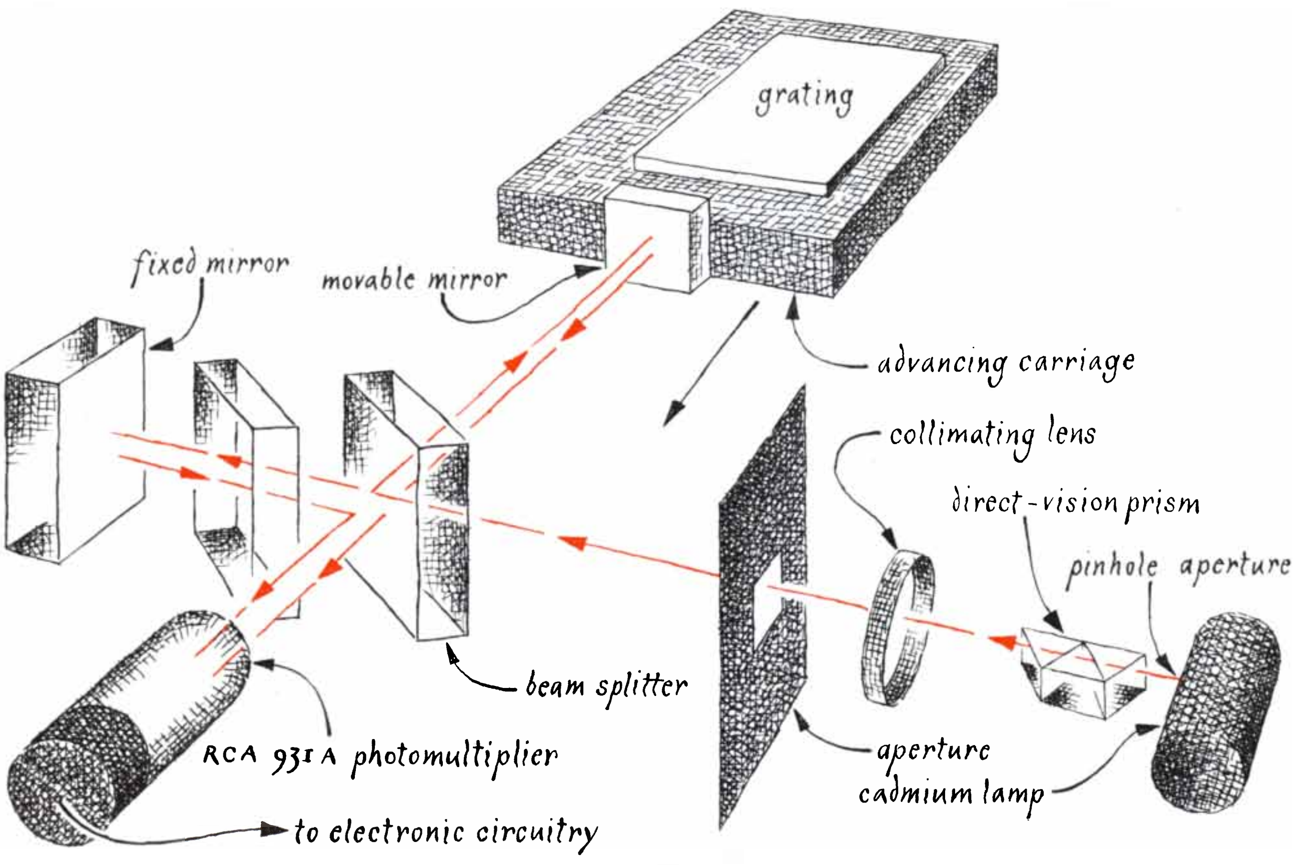
"Having developed the optical measuring system, I proceeded with the construction of the first version of the engine. The principle of its operation was simple and remained so as the engine evolved. The movable mirror of the interferometer is fixed to one end of the carriage that supports the grating. All other parts of the interferometer (indeed, all other parts of the engine except the driving motor, the stabilizing flywheel and the electronic components, including a regulated power supply) are mounted on a thick cast-iron base and are enclosed in an iron box with walls a quarter of an inch thick.

"The screw that drives the carriage is coupled to the motor through a magnetic clutch. During the return stroke of the ruling engine's ram the clutch is temporarily engaged to rotate the screw until the electronic circuit counts seven interference pulsations. On the count of seven the clutch disengages, thus positioning the aluminum film to receive the next groove. The operation is repeated automatically until the grating is finished or something goes wrong. Seven pulsations correspond to a carriage displacement of $66.14 \times 10^{-6}$ inch, or 15,120 rulings per inch. The interferometer of the first version of the engine usually went out of adjustment after about half an inch of the aluminum had been ruled. The main reason was that the slideways were not rigid or straight enough.

"The carriage slideway of the present machine consists of a straight steel bar six inches long and one inch square. This form was selected because it can easily be tested for straightness on an optical flat. I made three six-inch optical flats of Pyrex glass expressly for this purpose, although in the end the bar had to be finished by observing the tilt of fringes with the interferometer as the carriage traversed.

"Rotation of the carriage around the slide bar is restrained by outriggers carrying ball races that roll on straight cylindrical rails. A spring assembly on one of the outriggers can be adjusted to remove most of the weight from the slide bar. The lead screw has 26 threads per inch. It was cut on my three-inch lathe and lapped for smoothness, but no attempt was made to correct errors of pitch.

"At the end of a ruling stroke a cam on the crankshaft that operates the ram closes the electronic circuit. A second cam on the crankshaft communicates rotation to the input of an electrical clutch. The clutch rotates the lead screw through a train of reduction gears. After the required fringe count has been made electronically the clutch disengages. The angular rotation of the lead screw averages about .6 degree of arc per ruling.




*The interferometer of the ruling engine*

"The ram that carries the reciprocating diamond tool slides on a hardened bar of steel eight inches long and 3/4 inch in diameter. A friend ground the bar for me between centers on a precision lathe. The bar came off the lathe straight and cylindrical to within .0001 inch and required only slight lapping.

"The ram, consisting of an aluminum *L* section, is supported on the horizontal slide bar by four bearing pads of Graflon. This remarkable substance appears to be an intimate mixture of polytetrafluoroethylene (Teflon) and graphite. Not only does it have the lowest coefficient of friction of any solid but also its static coefficient of friction is lower than its dynamic coefficient. Therefore when Graflon slides, it does not exhibit stick-slip friction. The chattering movement that has been the bane of builders of ruling engines for more than a century is thus eliminated.

"The bearing pads were cut from a sample of Graflon that was donated to me by the Morgan Crucible Company. The crank that drives the ram operates through a rocking-arm linkage that I devised to conserve space on the baseplate.

"The diamond tool or stylus [*see top illustration at right*] does not cut the aluminum. It displaces metal sideways. The shape of the tool resembles the keel of a boat. The diamond is supported by a dop made of copper wire. A small hole to receive the stone was drilled axially in the square-cut end of the wire. Surrounding copper was then crimped over the diamond and fastened with silver solder. Excess metal was cut away from the mounted stone to expose areas that became the working facets.

"The tool bears on the aluminum with a force of only about a gram, but in effect the minute working facets exert a displacing force of several tons on the metal. I first attempted to use the natural faces on a crystal of Carborundum, as the American physicist R. W. Wood had done when he pioneered the production of gratings for the infrared portion of the spectrum. When this effort failed, I polished flat facets on the Carborundum with a rotating copper lap charged with diamond paste.

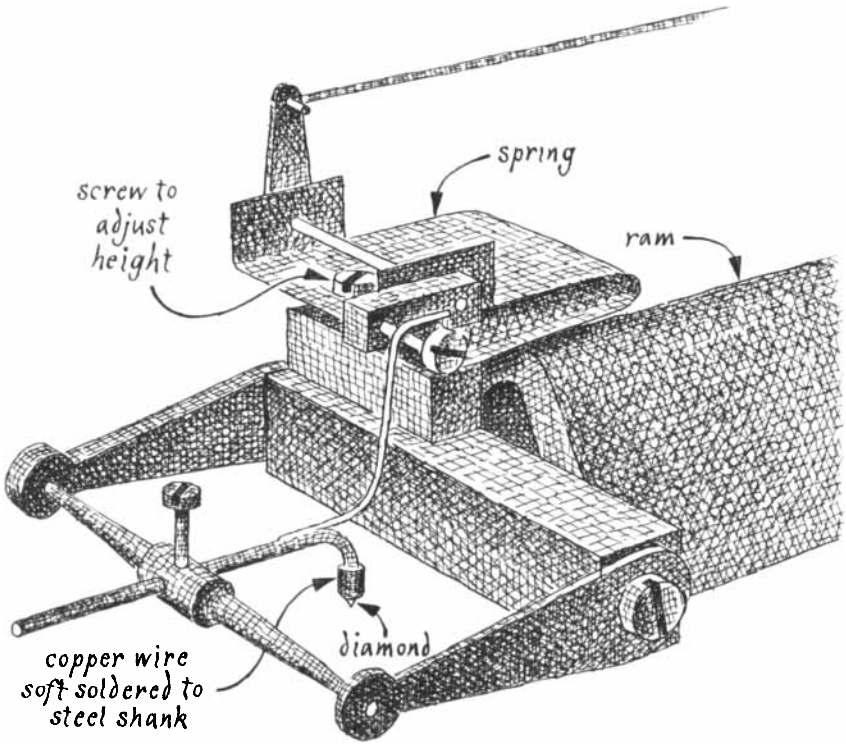
"My first good grating was ruled with one of these tools. Its dimensions were 5/8 by 3/16 inch. Although the grating was small, it easily resolved the *D* lines of sodium.

"Ultimately, however, I accepted the fact that a diamond tool is essential. I obtained a fragment of diamond from a shattered grinding wheel and fastened it to a mounting with cellulose cement. Through beginner's luck the resulting tool worked splendidly until the cement gave way.

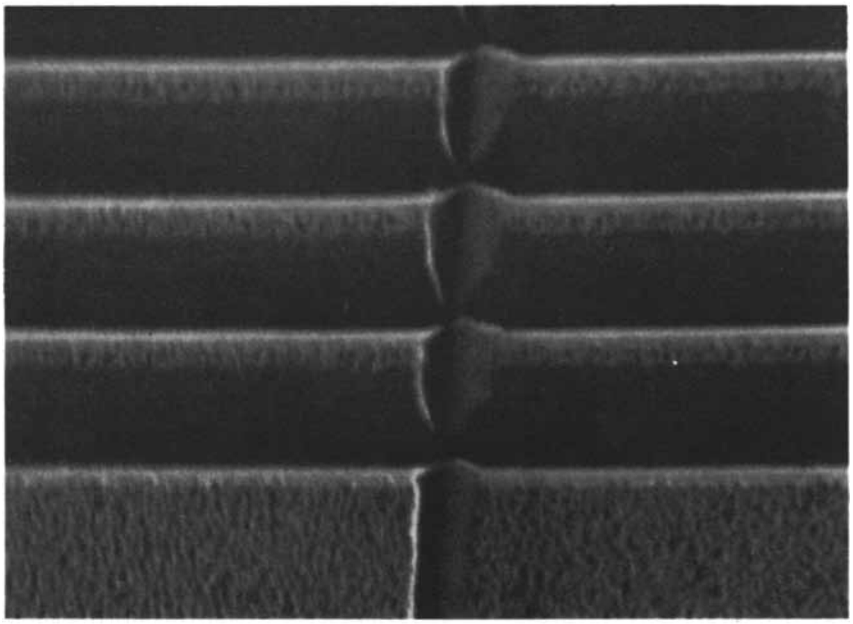
"I then attempted to cut facets on the diamond. The project almost drove me to distraction. The diamond consistently cut deep grooves in the laps, but no facets appeared on the stone. A visit to our local reference library produced the explanation. Diamonds can be polished in a reasonable length of time only if the direction of cutting is appropriately oriented for the crystal plane that is being abraded.

"The keel shape of the tool requires a minimum of three facets. The procedure for determining the cutting directions of each facet is complex and tedious. It is fully described in the technical literature.

"During the final stage of polishing




*The pivoted diamond tool*



*Scanning electron micrograph of rulings*

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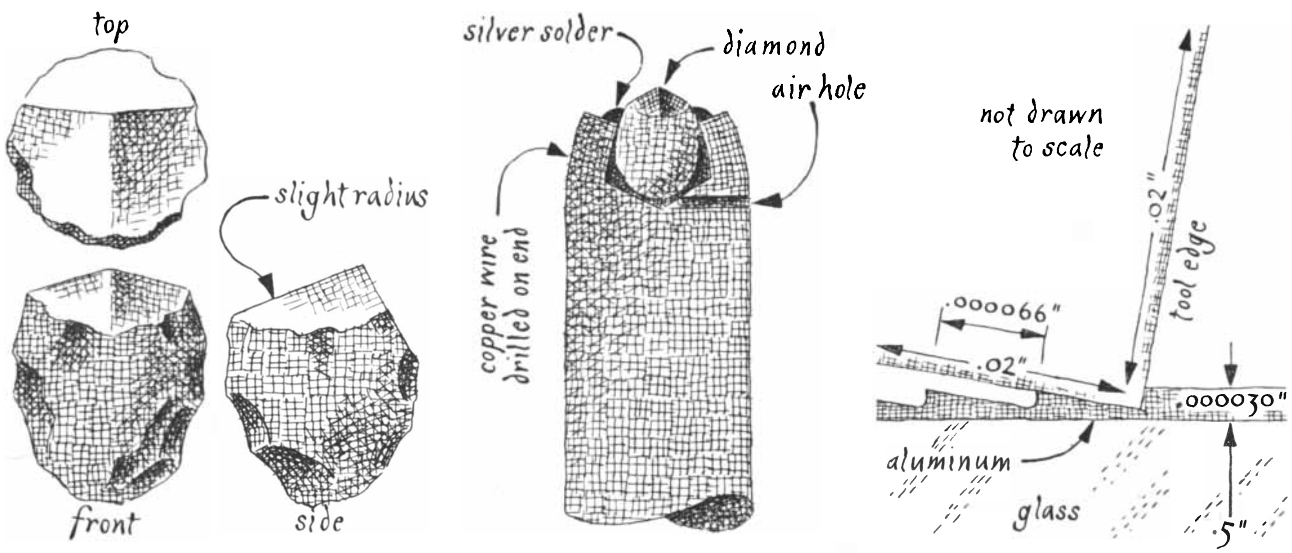
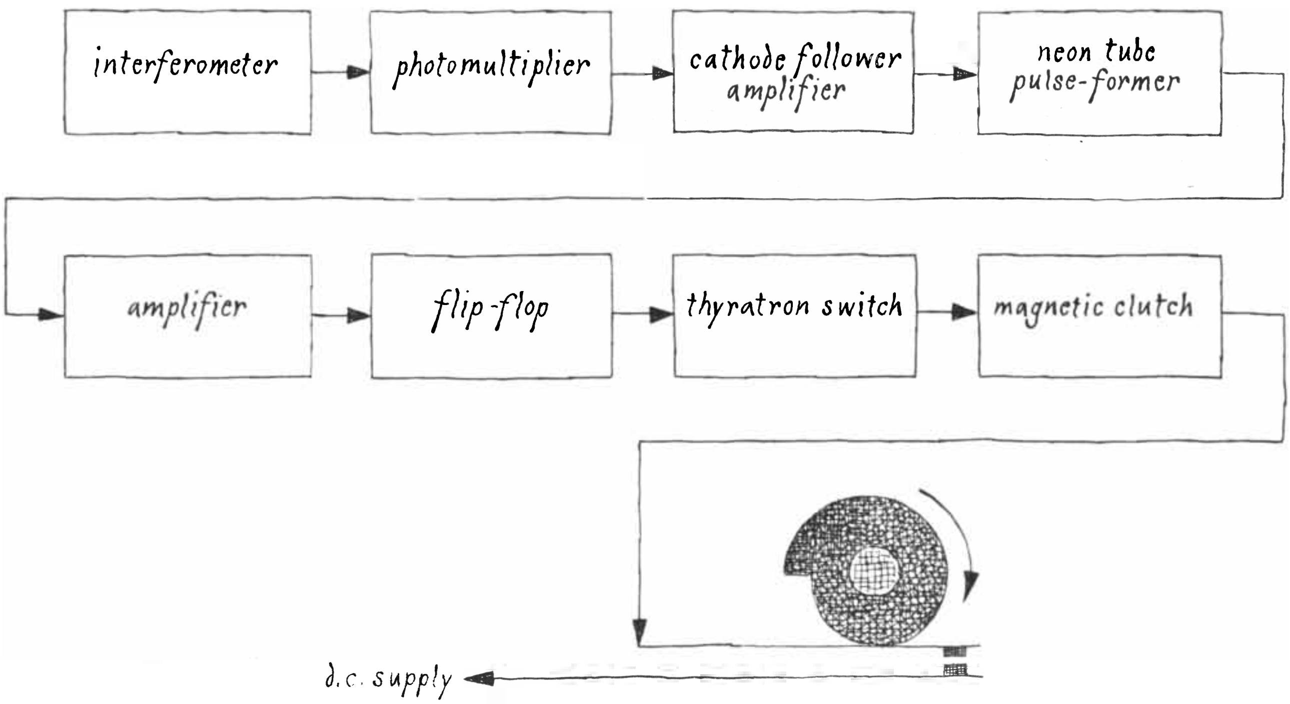
the facets are examined under a microscope with intense vertical illumination at a magnification of roughly 400 diameters. The intersecting edges of the facets should appear as perfect diffraction lines devoid of spots or thickening. The faceted diamond and its dop are assembled in the pivoted tool holder at an angle close to the desired 'blaze,' which is the slope where the reflecting surface of the ruled grooves concentrates maximum light in the spectral order of interest.

"The grooves of blazed gratings are saw-toothed in form. A grating of 15,000 grooves per inch, in which the reflecting surfaces are inclined at about 10 degrees with respect to the surface of the aluminum and with which the second surfaces make a right angle, is blazed for the first spectral order. Initially I place the diamond tool as close as possible to the calculated angle. Then I rule and test a small grating, readjust the tool accordingly and repeat the procedure until the required slope is closely approached by successive approximations.

"Rulings blazed for the first order that are 66 millionths of an inch wide are about 12 millionths of an inch deep. As I have mentioned, the tool makes grooves by deforming the metal. For this reason the aluminum coating should be at least 30 millionths of an inch thick to allow unrestricted plastic flow. I had difficulty obtaining films of this thickness from companies that specialize in coating mirrors, and so I set up my own aluminizing apparatus. It includes a six-inch bell jar, a pair of piston backing pumps connected in series, a diffusion pump and the kind of evaporating coils previously described in these columns [see "The Amateur Scientist," SCIENTIFIC AMERICAN, March, 1960].




*Details of the diamond tool*




*Arrangement of the electronic circuit*

"Incidentally, I devised an inexpensive valve for operation between the backing pumps. Experiments demonstrated that an oil film across a small aperture prevents the flow of gas at pressures of up to about two torr. To make the valve I inserted a piece of gauze between the pumps. The gauze is wetted with oil during each stroke. During the evaporation of aluminum the optically flat glass blanks are rotated continuously by a synchronous motor that revolves at the rate of 30 revolutions per minute.

"In order to prevent outgassing, the motor was thoroughly cleaned, rewound with 20 turns of thick enameled wire and lubricated with silicone vacuum oil. It runs on one volt and three amperes. I have no difficulty exhausting the system to a hard vacuum.

"Glass blanks were made originally by figuring rectangular pieces of plate glass. Unfortunately the errors of flatness and parallelism of the new 'Float' glass are so large that the material must be ground, polished and figured with the aid of an optical flat.

"The electronic system consists of the photomultiplier, an amplifier, a neon-lamp circuit that transforms the sinusoidal output of the photomultiplier into a series of flat-topped pulses, a flip-flop pulse counter and a thyratron switch that controls the magnetic clutch [*see lower illustration on opposite page*]. All these circuits use old-fashioned valves (vacuum tubes). Friends chide me for not switching to solid-state devices, but I am content to stick with my red-hot wires in glass bottles. They don't blow up if I make a wrong connection!

"About two days are needed to rule 45,000 grooves in an aluminized blank three inches long. The ram makes 16 strokes per minute. Variations in the temperature of the engine must be minimized throughout the 48-hour interval to prevent dimensional changes that would ruin the grating. I keep the engine in a room on the north side of my house. A bimetal thermostat and an electronic relay control an electric room heater. The thermostat is close to but not inside the housing of the engine. I do not attempt to rule a grating during extreme variations of outside temperature. The controlled heater confines the temperature of the engine to excursions of less than .1 degree Celsius.

"Variations of barometric pressure equivalent to one inch of mercury can cause an error in groove spacing of about 11 millionths of an inch per inch of grating length. The problem can be avoided by sealing the tank with a lid and a gasket and maintaining the pressure at 27.6 inches of mercury, plus or minus .003 inch. A small barometer in the tank is fitted with a photoelectric detector, which switches on a small pump to make up for leakage into the tank. The pressure is a little lower than the lowest barometer reading and ensures that the lid is always held on. The mass of the tank also averages out short-term temperature variations and damps vibration.

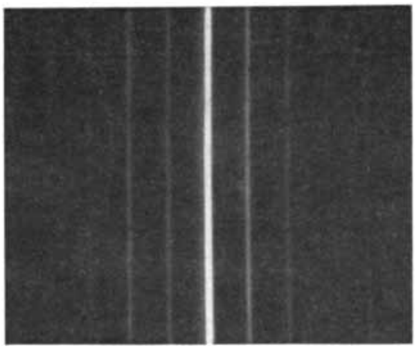
"To rule a grating I position a suitably prepared blank on the carriage. About 100 grooves are ruled to check the mechanism, including the action of the rocking-arm linkage that lowers the diamond into contact with the aluminum at the beginning of the ram's traverse and lifts it for the return traverse. The electro-optical system is similarly observed to ensure that the carriage is indexing in appropriate increments. Ruling is then stopped.

"The electric heater continues to operate for roughly 10 hours until all parts of the machine reach a predetermined temperature. The engine is then started, but ruling is delayed for 30 minutes. During this interval final checks are made of the adjustment of the mirrors of the interferometer and the output of the photomultiplier.

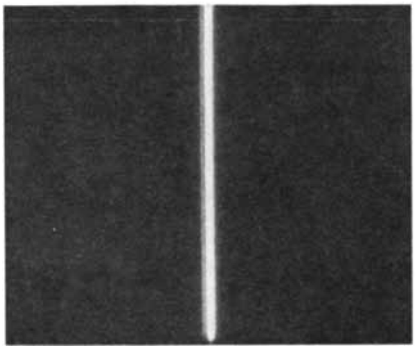
"To start ruling, the diamond is lowered. During the ruling procedure the output of the photomultiplier slowly decreases owing to fatigue of the cathode surface. Full output is restored at intervals by increasing the brightness of the cadmium lamp. The adjustment causes small but acceptable errors in the spacing of the rulings.

"Although the interference-control system is capable of detecting the position of the carriage within a hundredth of a fringe (a tenth of a millionth of an inch), it is not easy to construct a mechanism that will advance the carriage with this accuracy. Precision is degraded by the effects of friction, the uncertain driving action of the screw and nut and the elasticity of the metal. The cam that drives the magnetic clutch is shaped so that for each advance of the carriage the rate of fringe counting is initially high and decreases almost to zero as the last count is approached. Even so there is some random overshoot. These small errors can be tolerated because they are random.

"On the other hand, diffraction gratings that contain periodic errors of groove spacing display false spectral lines known as 'Rowland ghosts' that flank the parent line. An example is depicted by the accompanying spectrograms [*this page*]. The upper illustration displays the green spectral line of mercury at 5,460 angstroms together with flanking ghosts that are almost as intense as the parent line. This spectrogram was made with a diffraction grating that was ruled on an engine made by Henry A. Rowland at Johns Hopkins University. The lower photograph displays the same spectral line of mercury as diffracted by a grating that was ruled on my machine.



*Spectrogram with Rowland ghosts*



*Spectrogram without ghosts*

"Without interference control the gratings ruled on my machine would scarcely diffract recognizable spectral lines. Even with the control the engine is not without limitations. The carriage and the ram can rule aluminized blanks up to two by three inches in size, whereas the best professional machines accept blanks at least three times larger.

"One of the most difficult problems with my machine was confining the motion of the diamond to a single straight line as it reciprocates several tens of thousands of times. Putting a lubricant between the ram bearings and the slide bar introduces problems of variable film thickness. On the other hand, dry bearings operating at light loads acquire a high polish and start to wring, or adhere to the slide bar by molecular attraction. The Graflon bearing material shows a minimum of this effect along with low wear and freedom from stick-slip effects. Even so the ram is still subject to minute deviations."

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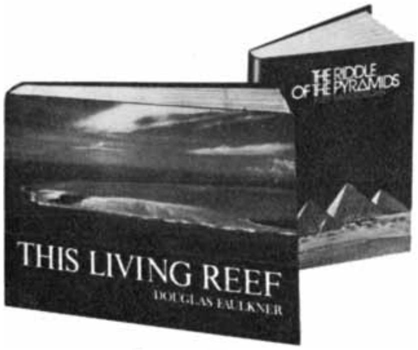


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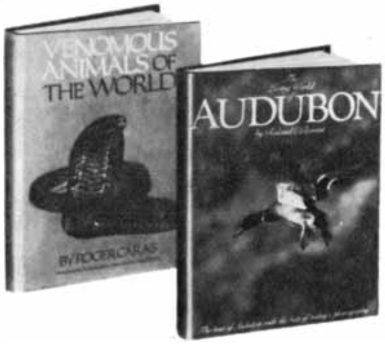


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# BOOKS

## *The Mound People of Denmark, aristocratic Bronze Age predecessors of the Bog People*

by Philip Morrison

The Mound People: Danish Bronze-Age Man Preserved, by P. V. Glob. Translated from the Danish by Joan Bulman. Cornell University Press ($12.50). The grazing lands of the Danish mainland lie open under the summer skies, the sea glinting often not far off. Small round-topped moraine hills mark the landscape, relics of the ice. Other mounds, man-made with pointed summits, dominate the natural moraine at a few thousand sites, most of them placed subtly just to one side of the highest point of the natural hill. These mounds are not heaps of earth or gravel but structures carefully built of cut turfs, supported at the base by a ring of stones or a wattle fence some 30 yards across.

For many years the mounds were cut into for fill or to accommodate the plowman. Then, 150 years ago, someone found an oak coffin in one mound, but "there was nothing except earth in the coffin." A few more mounds yielded up garments, bronze weapons, even hair (and gold or rumors of gold), but only in the 1860's were the first of the Mound People themselves brought to light. Meanwhile, 30 years earlier, one dank low fen had rendered up an uncoffined but wonderfully preserved body of a woman "dark as brown leather," her body and clothing preserved by the tanning action of the bog waters. The oak coffins in the mounds had once held human corpses; the hair wrappings, bronze swords, jewels were all intact, but the bodies were reduced to indistinct forms; the bones were gone, and in their place was only a "peculiar, pale blue powder."

The Bog People were poor, half-naked sacrificial victims. The Mound People, slowly revealed in detail by the spades of Danish archaeologists, were an aristocracy, much honored in death. Their costume and goods are richly revealing of quite another and earlier culture. In 1893 the 20-year-old girl of the Egtfed mound was carefully removed from her oak coffin at the National Museum. She was dressed in summer clothing: a corded miniskirt (made, like all her clothes, of brown sheep's wool), a short tunic and a bronze stomach disk on her bare midriff. At her burial a yarrow head in blossom was placed carefully beside her; the last thing put into the coffin was a birchbark basket whose layer of sediment revealed that it was filled with "a strong festive drink" between a beer and a fruit wine, brewed from wheat and cranberries, spiced with bog myrtle and containing honey.

In this brief, evocative book the author, Director General of Museums and Antiquities of Denmark, tells about the mound folk themselves and how the Danes of today came step by step to understand them. Photographs illuminate the graceful, lighthearted text, now showing the mound as it lies on the open land, now setting before you twice lifesize the bronze, intense figurine of a horned god. It is delightful to see the old line drawings made by Captain A. P. Madsen, "the museum's incomparable draughtsman," who recorded most of the digs until that day in 1891 when, with no time to wire for the captain, an excavator first wrote: "I do not know whether I should order a set of photographs for the museum (35 Øre each, mounted)."

The Mound People were a foreign aristocracy from the east who held the land for a long time, although the mound burials spanned only a prosperous century or two near 1250 B.C. They traded by ship with the Bronze Age world of the Baltic and the North Sea; their ships are drawn on the rocks everywhere. Their bronze and their gold, first as finished goods and later as metal stock alone, came from the eastern Mediterranean; there was no copper or tin in the north. For a long time they exchanged precious amber and furs for their metal, but probably their trade was balanced mainly by great herds of horned cattle that were driven south, and that are represented again and again as ox gods and ox men and in drawings of men mated with beasts and in the great horn-shaped trumpets, or *lurs.*

Above all the Mound People valued the sun and the horse. The wonderful bronze disk of the sun, seen as a horse-drawn chariot with one side shining in gold for day and the other side dark in bronze for the hidden night return trip, all of it rolling on three sets of bronze wheels, is the worked essence of their high culture. Since it was plowed up in 1902 it has become one of the most celebrated works of the Bronze Age, although it is less than two feet long.

The Bog People worshiped not the sun but the earth. It was she who claimed the victims of the preserving waters—and who ended the rule of the chieftains of the Mounds. Since the high-born traders ruled through their monopoly of bronze, once iron came within men's means the bog iron ore found all over the country slowly brought independence to the peasants and their smiths, and the rule of the Mound People and their descendants came to an end. The great bronze horns themselves were finally silenced, thrown out as sacrifices to the concealing powers of the damp lowlands.

An Electron Micrographic Atlas of Viruses, by Robley C. Williams and Harold W. Fisher. Charles C Thomas, Publisher ($17.50). Nowadays there is an obvious metaphor: a virus is a cassette of tape. The "cassette" is a more or less complex structure of protein that serves as a protective container even at its simplest and that may be elaborated with all kinds of fittings to adapt it for entry into the playback position within a specific infected host cell.

The atlas is an illustrated catalogue of these natural cassettes, 31 of which are shown in big eight-by-10-inch micrographs, cunningly magnified up to half a million times to display the very texture of the protein, although not its atoms. The shapes are varied. Influenza virus is almost cell-like, a long helix stuffed into a fringed envelope, a tenth of a micron across and not all protein; bacteriophage *fd* is a long, thin "flexuous" rod like a piece of string, only 60 angstroms across. Even the first electron micrographs of viruses in 1939 (the senior author was one of those pioneer micrographers) could confirm the physical chemists' inference of the rod form of tobacco mosaic virus (TMV) and reveal the spherical or tadpole forms of other viruses, but they could do little more.

The art is now mature. Here you can see TMV, its image six inches long, the rod plainly a helix with 131 distinctly layered rings and a narrow hollow along the axis. In another picture the fragile tape ravels out of the ends of some degraded rods, its elegant internal winding into the coils of the protective protein helix disturbed. Such rods will polymerize from a solution of the protein alone. Under comfortable conditions the solution contains mainly small three-monomer associations and some little "washers," each two rings of the helix. Make the solution a bit more acid and the long rods obligingly form; they are shown here, looking just about like the natural virus.

The best-mapped virus, the bacteriophage $\phi$X174, is a 12-spike protein capsule of middling size with a circular strand of DNA, a single helix. The DNA is known to code for eight proteins. Four of them make the capsule and the spikes, three are used for the replication of the tape and one encodes an enzyme that attacks the host wall; there is no room for much unaccounted-for information. This, then, is a recipe for a competitive life form of minimal complexity.

Quite different are the particles of TIV: *Tipula* iridescent virus. Its host is the larva of the crane fly. These particles—an eighth of a micron in diameter—take over the host's metabolism so thoroughly that the insect body fills with the virus material, becoming opalescent. The virions (virus particles) can be seen to be icosahedrons with relatively sharp corners; when they are purified, they pack to form opal-like, magnificently colorful pellets, "crystals" whose units are the virions. Electron micrographs of a freeze-dried TIV, shadowed by the evaporation of an electron-scattering metal layer over the specimen from two directions, closely resemble the shadows cast by a cardboard icosahedron. Not many other viruses are big enough and regular enough to yield such a protein analogue to the mineral opal, which is made of packed spheres of silica.

All the viruses here were micrographed in the Berkeley laboratory of Professor Williams, who used two commercial electron microscopes. The subjects arrived by mail or by hand from down the hall, thanks to many colleagues. The progress of the art owes much, of course, to improvements in the instruments, but much also to the cuisine of preparing specimens. Let a virus merely dry out of water solution and the "electron micrograph . . . is unimpressive." Contrast is low, the surface tension has flattened and distorted the object and inner structure is not seen. Evaporated metal films help contrast; techniques such as freeze-drying or passage through the critical point of a mixture of water and liquid carbon dioxide end surface-tension problems.

The fine micrographs shown here all employ one newer, remarkably simple technique: negative staining. The virus in water solution is mixed with a few-percent solution of a heavy metal salt such as sodium phosphotungstate. The mixture dries out on the thin specimen film. The dried layer now consists of virus particles embedded in the residue of the salt. Wherever the particle is hollow or has a surface indentation, a mass of the salt fills the volume once filled by water. Tiny concentrations of the heavy atoms scatter strongly and yield dark spots in the image. The contrast is now strong but negative. That is, where the organic material was thin or hollowed out there is more stain and a darker image. Where the organic material lies thick the stain is thin and the image lighter. Interpretation is a bit puzzling, but even stereoscopic mapping is possible. The same process had the serendipitous result of solving the drying distortion because the stain matrix becomes harder as the water leaves and helps to support the structure.

The interesting introduction to the atlas is an account of history, technique and nomenclature. It includes a brief discussion of the principles of the basically icosahedral or dodecahedral symmetry of those virions that are not helical rods or coils. The results are clear, if a little complicated, but their elegant basis in geometry is not given in enough detail for an uninitiated reader.

Students of virology will enjoy and consult the work. The general reader will find it striking: a visual presentation of the diversity of molecular arrangement in a domain where molecules are bound by rules lying between the general legislation of crystal thermodynamics and the individual commitment of the gene.

SCOTT'S LAST VOYAGE THROUGH THE ANTARCTIC CAMERA OF HERBERT PONTING, edited by Ann Savours. Praeger Publishers ($12.50). THE ARCTIC, photography and text by Fred Bruemmer. Quadrangle/The New York Times Book Company ($25). The little Dundee whaler *Terra Nova* entered McMurdo Sound about New Year's of 1911. Her commander, Captain Robert Falcon Scott, R.N., C.V.O., appears hand on sword hilt in the formal portrait frontispiece of this book assembled from prose and picture records of that expedition by the expert responsible for the Arctic Gallery of the National Maritime Museum in Greenwich. The text is well chosen, including both quite fresh material and such classic pages as those out of Scott's diary, which include his eloquent last words, written as his sick and exhausted party died on the ice after some 700 miles of man-hauling, just 11 miles short of their next supply depot. The photographs are new to us; they bring out of agency files about 120 of the black-and-white plates (and four surprising early Lumière colorplates) made by the expedition's photographer.

Ponting's plates are the work of a serious artist; their composition and variety demonstrate that. Their presence adds visual texture to the immediacy with which readers still come to the tragic story of the British Antarctic Expedition. Here is the ship at sea, crowded with Siberian sled dogs, 19 bad-tempered ponies shipped from Vladivostok, pet rabbits, three motor sledges and plenty of coal for the ship's auxiliary engine. The ship made water freely, Ponting noted, and "twice, daily, and once in the night watches, sixteen . . . officers and men together, would man this crank, and to the lively shanty, 'Ranzo, boys, Ranzo,' a flood of water pumped from the lip." (Coal had to be hoarded, and so they spared the steam pump.) This Edwardian expedition was clearly in transition to our epoch of polar exploration; the chantey seems archaic, yet here too is the slide show Ponting gave the expedition with a carbide projector, displaying shots of Fuji and of geishas that the globe-trotting photographer had made not long before. The motor sledges, small full-tracked platforms, failed after one week southbound; their design was clearly still halting in detail, but in the end their kin have inherited polar transport. The ponies were under the care of a Siberian groom and a devoted cavalry officer. The ponies hauled supplies south for the depots until "their useful life was over"; then they were shot and cached as dog food. Dogs alone hauled the Norse winner of the South Pole race: Amundsen went swiftly south with more than 50 dogs and returned with only 11, but with all four of his companions, "men and animals all hale and hearty."

The faces of the men of the *Terra*

*Nova*, furling mainsail, cooking, tending their animals, are shown, as are crystalline vistas of the ice pack, the ice foot along the shore and the mountains of the desert continent. The expedition brought along a full cargo: the culture of its country and its time, from self-conscious gallantry and a morning-glory phonograph, with a dog posed beside it, to the banter and parodies of its little newspaper. Ponting escaped death once when he jumped onto an adjacent ice floe just as eight killer whales (some are shown here) in concert broke up and rocked his floe. Today it seems possible that the killers desisted once they saw a man was threatened, but in those days such a thought was impossible. The voyage seems to have been ruled by fear of uncertain dangers and an unnecessary acceptance of some that were all too sure. Ponting returned with his plates and his motion-picture film, a film never exhibited in full until 1933, two years before his death.

Fred Bruemmer is a gifted photographer of our times, and his colorplates are reproduced dazzlingly in *The Arctic,* some across a two-page spread two feet wide. He has traveled in the Arctic, a shore peopled by a remarkable set of human beings, ever since 1950, when he came to Canada as a Latvian immigrant. He has spent a season in Spitsbergen, a year among the Lapps and 11 years in North America from the Aleutians to Greenland. Between travels he writes prolifically from Montreal, where this fascinating big volume was made.

The impact of these photographs induces the reader to hold his breath as he turns leaf after leaf. Now we see in black and white—for this subject exactly right—the smooth water of the bay near Thule in Greenland, six low white kayaks in procession hauling home a newly taken narwhal, white bergs gleaming in strong contrast behind the thin line of the hunters. Again we pause, struck by the brilliant red in the tall hats, the upturned shoes and the wide skirt hems of a Lapp wedding party. Or 75 ungainly walruses of the Alaskan coast sprawl on one another, their gleaming tusks white finials to the reddish golden, furry, slothful forms. Across one spread tiny figures of gleeful Eskimos engage in a tug-of-war, all background removed to a frieze-blank whiteness. Another picture shows the same game close up: seven real women at Baker Lake, their hoods and boots colorful, pulling hard on the thick rope. There is a shot of the bleak island where Frobisher came in Queen Bess's day and took home a load of fool's gold, and a graffito engraved very elegantly in 1767 on a rock near Churchill by the explorer Samuel Hearne.

The text is personal and learned by turns. There are six chapters on the history, the land, the sea, the plants, the animals and the people. There are inserted as well some 15 pages on special points such as insulation, a study of fur and blubber, and shamanism. Overall there is an air of quiet melancholy. "A certain pessimism and sadness pervade [the] text"; the old harmonious ways are going. The text and pictures mainly look back; only one diesel vehicle appears, on a Greenland road next to a sign warning "Watch out for dogsled!" There are no radar dishes or oil rigs; we see lichen, bear and musk-ox, bones of beasts and of men, glowing ice and turquoise shadows, huts, igloos, camps, hairy poppies and a white gyrfalcon.

The Eskimos are living on welfare checks now in Canada. Their teeth are bad because there is little fresh meat. Their whale-hunting villages began to disappear as long ago as the 18th century, perhaps because the whalers of Europe and America had so depleted the northern Leviathan. The people remain, however, a link across time to the days when all human beings lived by hunting and by gathering plants like the tall angelica, which is still the delicacy of the Eskimos near Thule.

In the northernmost village of the world, just beyond Thule, Bruemmer lived with an elderly couple. The old hunter "liked to tell me about his people's past." On request once he made the string figure he called *kiligfagssuk*, which sounded like what another man thousands of miles away had called the one he had once made for Bruemmer. In the west it was called *kilivaiciaq*. The figures were identical and the name was similar, although there has been no contact between the regions for at least seven centuries. What is the figure? It is a very large animal, with four legs, like the musk-ox but much bigger. "It existed a long time ago. No one here has ever seen it. Even the oldest people have never seen it." In this figure is preserved the cunning of the Siberian hunters who, 10 millenniums back, first represented the mammoth, the shaggy elephant of their snows.

A Source Book in Medieval Science, edited by Edward Grant. Harvard University Press ($32.50). By now most general readers in science know directly at least a little about the words and look of the fateful volumes out of the years between Copernicus and the aged Newton, six generations during which the Renaissance blossomed and the Baroque bore the fruit of modern science. For the millennium before that, however, the general reader who is not familiar with languages other than English remains largely illiterate.

Yet something did come before. In this anthology the learned editor (with some help from his friends) has assembled 190 selections (some of them nearly complete small treatises) from about 85 authors on science and medicine (but not technology) in the Frankish West. A plot of the papers against time is revealing: there is a scattering across the centuries from the end of antiquity through the 900's; the count begins to rise (with some Islamic authors) in the 1000's. It reaches a peak in the 1200's and 1300's, when, with the illustrious Thomas Aquinas and Nicole Oresme (both represented), the university masters flowered at Paris and Oxford (although they had come from as far away as Poland and Sicily). A few selections continue beyond that; Blaise Pascal neatly caps the medieval story when he proves "that nature has no abhorrence of a vacuum, nor does anything to avoid it," and replaces "that imaginary cause" by "the weight of the mass of the air."

Almost all these documents were written for manuscript circulation. The bulk of them enter this erudite but readable and well-annotated anthology in 20th-century translations of printed Latin versions that were published in Italy in the high Renaissance. About half of the papers (many translated by the editor) appear here for the first time outside of Latin or Greek. Three periods are well represented. The early Middle Ages weigh in with a few selections from the influential hack compilations passed down from sources that were themselves popular Hellenistic handbooks and compilations. These are the so-called Latin encyclopedists. (Diderot, forgive us!) Next Europe received actual translations of the Islamic treasure. Arabic versions of Greek authors, and some Greek texts too, were put into Latin. "Lest master Gerard of Cremona be lost in the shadows of silence," his admiring students wrote in Toledo after he died there in 1187, "all the works he translated... have been diligently enumerated by his associates" at the end of a book of Galen's. From Gerard we have Euclid, Ptolemy, Galen, Al-Khwārizmī and more. Then follows the bulk of the volume, the elaborations of the late Middle Ages.

A couple of tidbits must suffice for the massive whole. Here are a few chapters from *On the Art of Hunting with Birds,* by Frederick II of Hohenstaufen, the Holy Roman Emperor. He wrote on the structure and habits of birds in a brilliantly observed work just before 1250. In the preface he says: "We discovered by hard-won experience that the deductions of Aristotle, whom we followed when they appealed to our reason, were not entirely to be relied upon.... In his work...we find many quotations from other authors whose statements he did not verify.... Entire experience of the truth never follows mere hearsay." His Imperial Majesty was a prodigious figure and is a worthy favorite of the editor's.

Then there is the *Ymago mundi* by Pierre d'Ailly, a theologian who was greatly influenced by Oresme. His little treatise of 1410, on the geography of the world for students of Scripture, was later printed and became Columbus' bedside reader for some years before the voyage of 1492; the Admiral's marginal notations are included here with the translation of the text. Columbus particularly liked d'Ailly's view, misquoted from Aristotle and cited against Ptolemy, that "a small sea lies between the end of the western side of Spain and the beginning of the eastern part of India." Ockham's (or Occam's) razor is rendered here from an ascribed work, not written by William of Ockham himself but in his usual form: "It is futile to accomplish with a greater number of things what can be accomplished with fewer." It is interesting to read the letter written by Petrus Peregrinus, from his engineer's post "in camp at the siege of Lucera... Anno Domini MCCLXIX," which gives the first real account in Europe of the lodestone and the compass. Peter does a fine job, helpful and detailed, but ends with a careful design for a magnetic perpetual motion machine. The Alfonsine Tables for the sun and the moon are here, prepared in this form about 1327 and printed in 1483, with the old instructions and a modern example of their use. They were the European standard from about 1300 to Kepler's time.

Mathematics reads well to a modern eye, as in excerpts from the pretty advanced number theory of Leonardo of Pisa (we call him Fibonacci), the leading mathematician of the Latin Middle Ages, written about 1240. Medicine, for example advice to physicians about their behavior toward patient and family, often sounds like good sense today. The natural sciences are saturated with credulous citations but sometimes stand clear and fresh, as in the case of Theodoric's rainbow model of about 1300. Logic is hard going then as now, but it was subtle enough then. Taddeo Alderotti, writing just about 700 years ago, describes the repeated distillation of wine to yield *aqua vite*, which he was the first to prescribe to grateful patients. "It is able to cure virtually all cold afflictions, if you know how to use it," he wrote. "A half spoonful every morning, taken on an empty stomach, together with a small dipper of fragrant wine, makes a man glad, merry, and happy." The distillation process had been developed in Salerno, the seat of a famous school of medicine, not long before.

A FIELD GUIDE TO THE FERNS AND THEIR RELATED FAMILIES OF NORTHEASTERN AND CENTRAL NORTH AMERICA, by Boughton Cobb. Illustrated by Laura Louise Foster. Houghton Mifflin Company ($3.95). The ferns are the oldest familiar plant venturers into the inhospitable air. Like the seeded plants, they possess a specialized circulatory and support system by which they can rise to, say, the six feet of the royal fern, far above the other ancient plant group, the mosses and their kin. The ferns are not quite free of the bond of external water, however. Whereas pollen can fly dry as dust, and so can sexless fern spores, the sperm of the tiny sexual phase of the fern must propel itself within a film of water to reach and fertilize the egg.

The region described in the title of this handy and inexpensive paperbound field guide (a few pages sketch also the kindred plants found in Britain and western Europe) supports 100 or so species of fern and a few more of related orders, such as the club mosses and scouring rushes. They are here, logically keyed, described and delicately pictured in careful, small, pleasing line drawings. The book is meant for carrying to the woodlands in the pocket and consulting there; for instance, it presents the appropriate drawing on the page facing every description of a species. There is a helpful apparatus: binary keys, little essays on the wider view of the botanist and the paleontologist, a set of identifying drawings of the fruit dots of the various genera and the like. The volume, a reissue of the book first put out 20 years ago, is a bargain, and a key to a kind of botanizing that ought to be practiced more. The ferns and their kin are attractive, ubiquitous and wonderful; they sharply recall Devonian time, when life first bravely explored the land, and the time of the coal forests, when club mosses rose like giant oaks.

This fern guide is one of a long series of handbooks that now contains 21 titles, each a thoughtful guide to direct specific observation of a rock or a tree, a shell or an animal track, a star or a salamander. The overall editor, himself the illustrator of six members of the series, is Roger Tory Peterson. Peterson's devoted, firsthand and talented portraits of birds (and later flowers) in color grace the first volume of the series as they do a recent guide to Mexican birds done with the expert collaboration of Edward L. Chalif. Over the span of a generation Peterson has placed happily in his debt almost every American who has been caught by the specificity of the life visible around him.

THE INGENIOUS DR. FRANKLIN: SELECTED SCIENTIFIC LETTERS OF BENJAMIN FRANKLIN, edited by Nathan G. Goodman. University of Pennsylvania Press ($3.95). A bargain paperbound reprint (the right Philadelphia style) of a collection first published in 1931, this little volume presents brief letters and papers by a remarkable dreamer and practical man who was at once entrepreneur and revolutionary. The punctuation and spelling remain as in the original except that the abundant unnecessary capital letters have been suppressed. The writings are practical and theoretical, deductive and empirical, farseeing and occasionally wrongheaded, but everywhere lively. Consider bifocals, which Franklin invented and figured. Since they make visible the features of the speaker, "I understand French better by the help of my spectacles." When, about 1740, the Boston newspapers reported clear skies at the time of the lunar eclipse although Philadelphia was beclouded by a severe northeaster, Franklin wrote to his brother in Boston. The storm had held off there, he learned, until after the eclipse. Thus did we first realize the usual course of such storms: from the Gulf of Mexico toward Halifax, even though their winds come from the opposite direction. Here are many ways to use *mayz*, from corn on the cob to corn bread, corn syrup and succotash; how to make that famed kite, and how to let a kite draw you through the water while you swim; a "magically magical" square of 16 rows and columns; an eyewitness account of the first hydrogen balloon and the first two manned flights; a letter to Priestley describing marsh gas; around 55 pieces in all, four pages long on the average.

This little book is a diverting scientific bicentennial document. Let us drink to Dr. Franklin as the year speeds by as once he proposed "the healths of all the famous electricians in *England, Holland, France,* and *Germany*...to be drank in *electrified bumpers*."

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


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