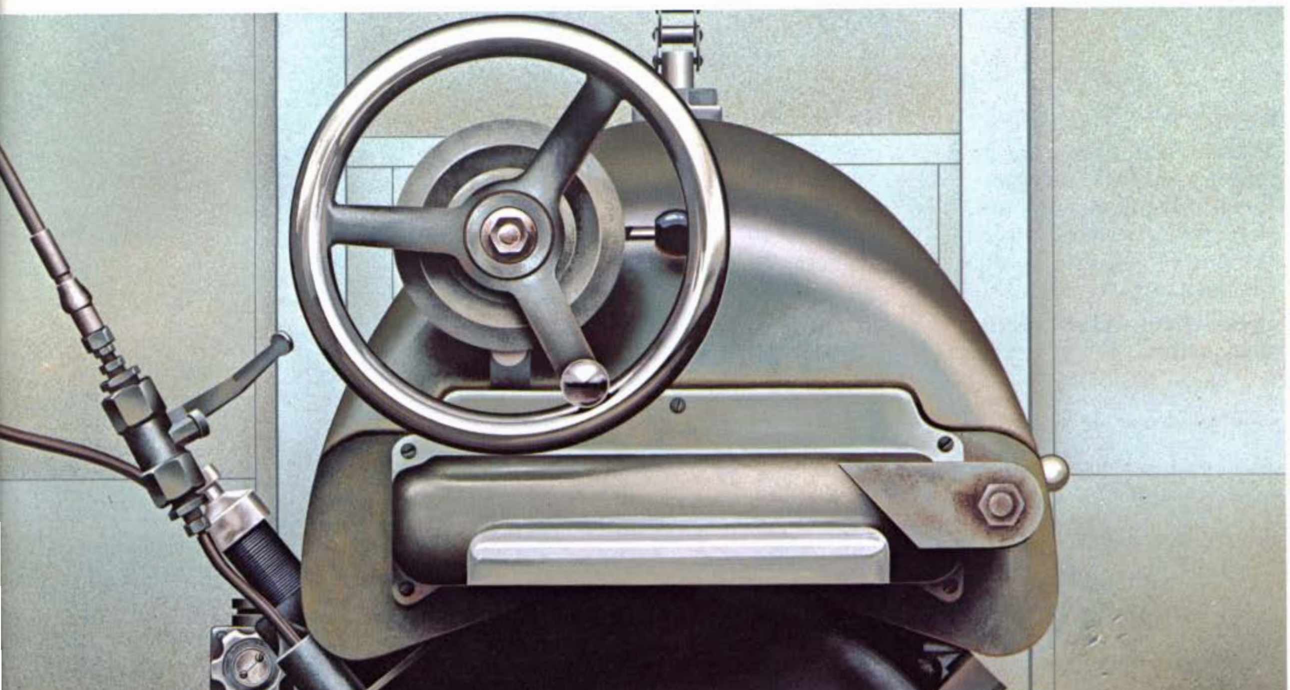
SCIENTIFIC AMERICAN



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November 1978


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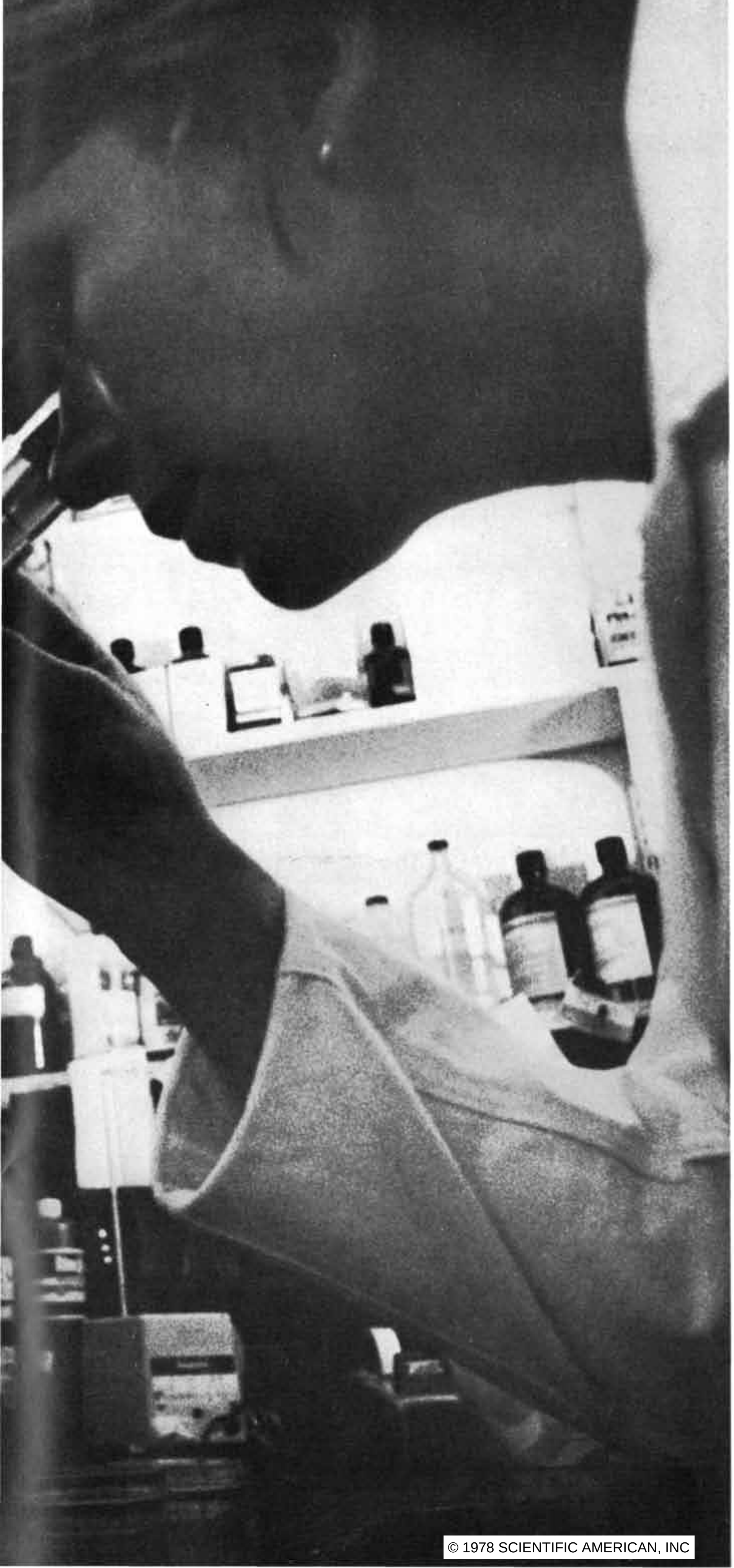
Established 1845 **SCIENTIFIC AMERICAN** November 1978 Volume 239 Number 5

ARTICLES

DEPARTMENTS



THE COVER

The painting on the cover portrays the work area of a grinding machine, one of many types of machine employed in industry to shape and finish metal parts by abrasive machining (see "The Mechanisms of Abrasive Machining," by Leonard E. Samuels, page 132). This machine is a surface grinder, which moves a steel part or a series of steel parts, mounted on a table, back and forth horizontally under a spinning grinding wheel to provide a surface finish of precise dimensional accuracy and flatness. The grinding wheel is made of bonded particles of aluminum oxide. As the workpieces (the parts being ground) move back and forth, their top surfaces and the surface of the wheel are kept relatively cool by a coolant, which also serves to some extent as a lubricant; it is the pinkish liquid. The small handwheel at the top is employed to adjust the location of the grinding wheel vertically in relation to the workpieces.

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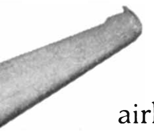
You'd expect McDonnell Douglas to build the super quiet DC-9 Super 80.

...but would you expect us to help you put your projects on Spacelab, insulate ocean-going tankers, or keep books for doctors?



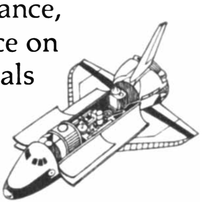
The new DC-9 Super 80 is coming. And you'll be able to see it long, long before you *hear* it.

Our new Super 80 is expected to cut the high-noise area around airports to as little as one-fifth of what it is with current jetliners of comparable size. With powerful, yet efficient, new engines, and improved instrumentation for all-weather operations, the Super 80 offers airlines the lowest operating cost per seat mile of any jetliner in this class.

And it offers you, the passenger, the comfort of improved ventilation and lighting, a much quieter ride, plus the on-time reliability you've come to expect from the DC-9 family of jets.

Our new Super 80 will fly in the early 1980s... and so will Spacelab...

Under contract with NASA, we're working with scientists and private industry to put research and manufacturing projects into orbit aboard the European Space Agency's Spacelab. The potential is as limitless as space itself. New life-saving drugs, for instance, difficult to produce on Earth. And silicone crystals for electronics components—with a purity never before achieved. To put your projects into orbit, we're the ones to call.



Our "floating pipeline," another project with roots in our space work, offers help in solving world-wide energy problems. Developed in cooperation with Gaz-Transport of France, it's an insulating system for sea-going tankers which keeps natural gas in super-cold liquid form during transport. This system, that saves space on ships, offers cost savings to shipbuilders and owners, and eventually, to users.

Just as our aerospace technology has produced some quite remarkable down-to-earth benefits, so has our computer technology...

You may have noticed—your doctor has not escaped the paperwork avalanche. Insurance and other report forms to be filled out. Financial accounting which grows more and more complex. Records of all kinds which must be kept available. Expensive paperwork which adds to the cost of your medical care.

That's why you'll welcome, as doctors do, our new Physician Data Services—a fully-computerized accounting and records system for medical groups and clinics. It not only gives *you* instant answers to questions about your account, it also gives your doctor an accurate, automated answer to his paperwork problems. And that can help keep your medical care costs down.

Finding answers is the work we do at McDonnell Douglas. And while we're an aerospace company, building jetliners, fighter planes, and space systems, we're also building on our aerospace technology to help find answers to the needs of people everywhere. If you'd like to know more about any of the work we've discussed here, just drop us a note. Address: McDonnell Douglas, Box 14526, St. Louis, MO 63178.

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LETTERS

Sirs:

Charles M. Rick's interesting account of *Lycopersicon esculentum* ["The Tomato," by Charles M. Rick; SCIENTIFIC AMERICAN, August] contained one curious omission: the variety *supermercati,* popularly known as the plastic tomato. This cultivar has become the overwhelmingly dominant type of market tomato; its distinctive flavor has been described by some knowledgeable investigators as resembling slightly acid cotton. Of its texture the less said the better.

Commercial tomato growers will no doubt be pleased to learn that current research programs promise to improve the fruit's yield, color, soluble solids and "machinability," the final word suggesting, perhaps appropriately, that we are dealing with some sort of man-made structural material. The rest of us would be even more interested to learn when, if ever, agricultural research will provide us with a market tomato that is fit to eat.

ROBERT CLAIBORNE

Truro, Mass.

Sirs:

In decrying the quality of fresh tomatoes in most U.S. markets Mr. Claiborne unquestionably touches on a serious problem. The fact is, however, that many people do not buy tomatoes for the table in supermarkets. They either grow them themselves or buy them from local sources in season, and for the rest of the year they abstain. Even so, the fault does not lie, as Mr. Claiborne and many other misinformed critics contend, in the breeding of market tomatoes or in the methods by which they are grown.

Market tomatoes of high quality are being grown throughout the U.S. In sound, unbiased comparisons taste panels have not shown any significant preference for the older cultivars over the modern ones. The problem is not production but delivery. The quality of market tomatoes in the "good old days" is perceived as being superior because they were sold only locally in the short growing season. Now the American consumer is accustomed to year-round availability, made possible by modern transport and off-season production in California, Florida, Texas and Mexico. The best available cultivars will not survive such shipment unless they are picked in the mature green or breaker stages and ripened in transit. Such practices, as I trust my article indicated, result in inferior quality.

Local production can solve this problem. In the growing season high-quality field-grown tomatoes can be delivered at reasonable cost. In the rest of the year crops of good, although perhaps not top, quality can be produced in greenhouses at formidable cost. It is questionable whether many consumers will pay the price of such a luxury item.

Another widespread misconception is that cultivars bred for machine harvesting and bulk handling are being delivered to the supermarket on a large scale. Such cultivars are grown almost entirely for processing. These firm, durable types have satisfactory quality for this purpose, as numerous evaluations and the wide acceptance of tomato products have demonstrated.

Contrary to Mr. Claiborne's opinion, growers and other segments of the industry are much concerned about the quality of market tomatoes, and they are investing substantial funds in research for the improvement of such tomatoes. I cannot elaborate on these projects here, but I shall be glad to furnish details to interested parties. The prospects appear bright for a genetic solution in the development of cultivars that can be harvested in a more mature condition and yet will withstand the abuses of transport and distribution.

CHARLES M. RICK

University of California
Davis

Sirs:

Lorus J. and Margery Milne ["Insects of the Water Surface," SCIENTIFIC AMERICAN, April] gave an interesting account of the four types of insects (water striders, whirligig beetles, backswimmers and springtails) that utilize water surfaces. I have discovered that a common duck louse (*Trinoton querquedulae*), one of the fastest-running lice on land and on waterfowl plumage, also moves rapidly and directionally on water surface films in response to ripples.

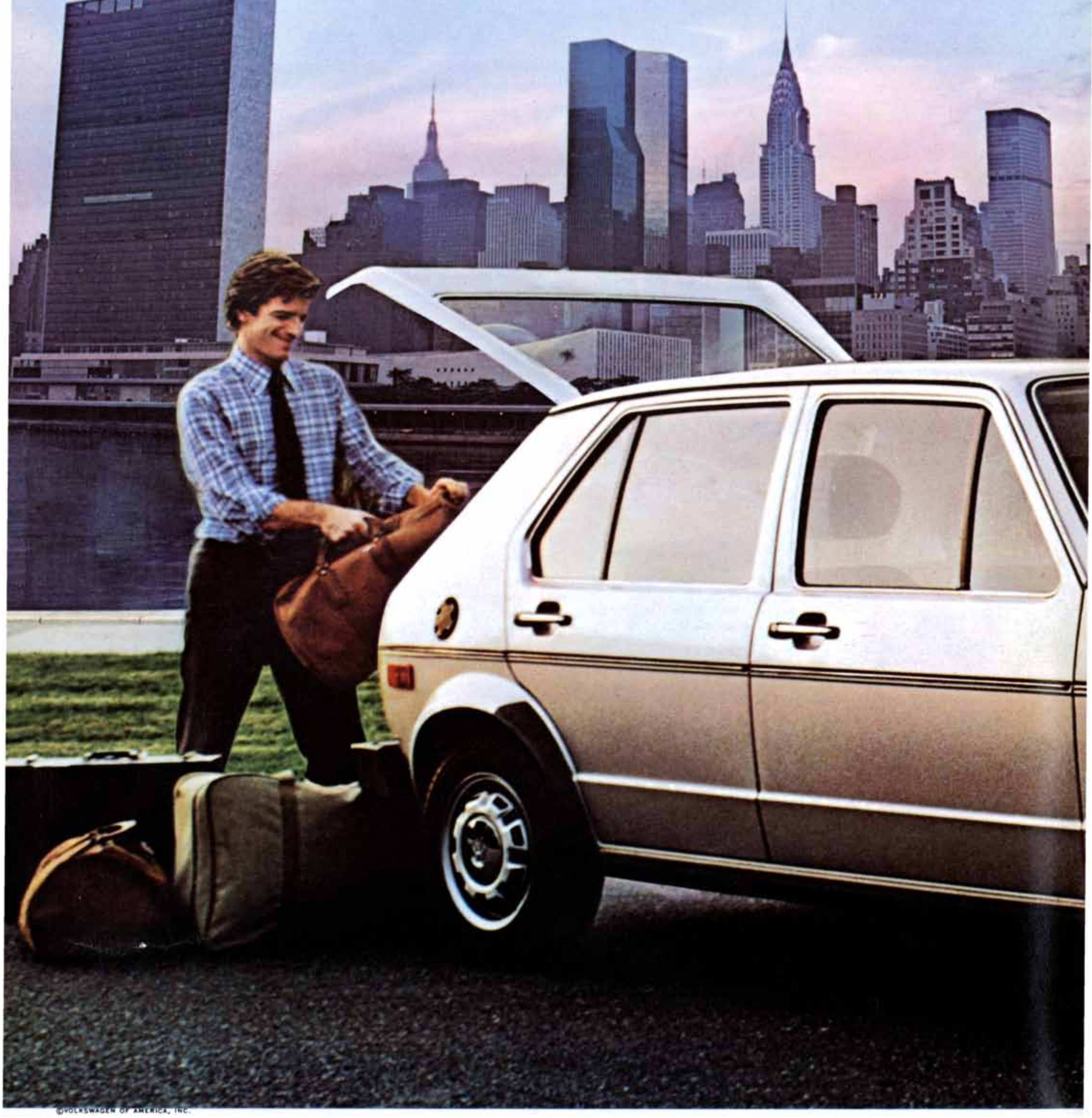
If this louse is preened by a waterfowl onto the water or knocked off in a landing or a dive, it can return to a suitable host by running on the surface film toward the disturbance created by the duck. This large (six to seven millimeters) mobile louse lives in low numbers on waterfowl (an average of four lice per bird), and I believe its mobility on the surface film is both interesting and important to its survival. It is thought that similar behavior will be found in some of the other Mallophaga of aquatic birds.

WARD B. STONE

Delmar Wildlife Resources Center
Delmar, N.Y.

Sirs:

"The Earliest Precursor of Writing,"



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If you're thinking of seeing the U.S.A. in a Chevrolet, think again.

If you're driven to driving coast to coast in a Datsun, hit the brakes.

Fact is, no other car in America can go from New York to L.A. on as little fuel as our Rabbit Diesel.

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by Denise Schmandt-Besserat [SCIENTIFIC AMERICAN, June, 1978], offers a lucid account of the hypothesis about the origins of cuneiform script that she advocates.

The ancient Sumerian lexicons may be able to partly close two of the gaps in documentation left by her work. In the ancient dictionaries ("Old Babylonian Lu," recension A 466–467 and recension D 307) we find lú na$_4$ na, "man of stone(s)," and lú im na$_4$ na, "man of clay 'stone(s),'" listed along with other accountants. The presence of these professions in the lists that come from the city of Nippur and elsewhere in ancient Sumer shows that the use of "stones" in bookkeeping was known in Sumerian at a period hundreds of years closer to the invention of writing than the Nuzi texts to which she refers, and in Sumer itself, where most scholars presume cuneiform to have originated. The references make it clear that the term "stone" was conventional, and that the tokens employed could indeed be made of clay, as were the actual objects studied by Schmandt-Besserat.

The Sumerian texts thus lend support to her interpretation of the tokens, and to her attractive hypothesis for the origin of writing.

STEPHEN J. LIEBERMAN

University Museum
University of Pennsylvania
Philadelphia

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

NOVEMBER, 1928: "Into the North across icy wastes and frozen seas the airplane flew on a noble errand. Weeks of silence followed. The world waited, hoped, searched. Then came the discovery of a part of the plane floating in the ocean, mute testimony of disaster. Roald Amundsen and those who were with him were lost. This modern Viking, eccentric at times, both beloved and criticized but always hailed as a man of iron courage and indomitable will, had come forth from retirement and had flown to the aid of the survivors of the dirigible *Italia*. When Amundsen was but a boy, he, to use his own words, 'irretrievably decided to be an Arctic explorer.' He trained rigidly until his body was a marvel of physical perfection and hardened almost beyond belief. Thus in later years he was able to conquer, with slim resources, in the fishing smack *Gjoa*, the Northwest Passage that had defeated others who had the resources of governments behind them. He was the first to reach the South Pole, was the first to attempt an airplane flight to the North Pole and was a member of the first party to reach the North Pole in a dirigible."

"Is there a planet beyond Neptune? Many attempts have been made to find such a body from the perturbation of Neptune and of Uranus, as Neptune itself was found by means of the perturbations of Uranus. The general outcome of these investigations indicates that an outer planet, if it exists, must be rather small—probably considerably smaller than Neptune and too small for its attraction to produce sensible disturbances of the inner planets. Such a planet might nevertheless easily be within the range of brightness accessible to modern photographs with instruments of moderate power. A search for it by the photographic method would be well repaid. By taking plates on consecutive nights, and comparing them with the blink microscope, the planet's motion would become conspicuous and could be picked out at a glance."

"Occasional press reports relate the results of experiments in radio control of moving objects—automobiles, airplanes and ships in particular. One of the latest deals with the maneuvering of a German battle-ship controlled from another ship. These gradual developments may have a far-reaching significance. True, in the present state of the art radio control of battle-craft from an enemy base could be combated by a radio 'barrage' and would also be dependent to some extent on weather conditions. But as research progresses who can say what discoveries may be made with the ultra-short waves, wave-changing devices and other means of combating these deterrents? Radio may become a vital factor in the events of the world apart from its use as a means of communication."

"When Gregorio Villalobos, the governor-general sent to rule New Spain, landed near Vera Cruz in 1521, he took from his ship some Spanish calves. Their descendants, the famous longhorns, thrived in the New World, spreading over Texas and the Far West. The longhorns were long on horns, legs and speed but short on beef, and they gave way to gentler, meatier breeds. Recently two forest agents were provided with a small appropriation to buy a few longhorns before the breed wholly disappeared. After a long search down in the prickly-pear country they found 10 cows and a single bull. Then they combed the great range country between Houston and Beaumont and found two more bulls and 10 cows. They have shipped the lot off to the Wichita National Forest for the building of a modest herd of 250 or 300 head. And so the Texas longhorn at the 11th hour is saved from total extinction."

SCIENTIFIC AMERICAN

NOVEMBER, 1878: "The announcement that Mr. Edison has discovered a means for dividing the electric current indefinitely, thereby making it possible to use electricity for lighting small areas, has had a marvelous effect in bringing down the value of gas stocks. But what is Mr. Edison's discovery? A few words will suffice to give an idea of it. It is based on the well-known fact that a wire can be heated by an electric current. The reader may have seen the gas jets of the dome of the Capitol at Washington. Over each burner is placed a coil of platinum wire, which, when heated by an electric current, ignites the gas. Mr. Edison uses the coil itself as the source of light, the current sent through it being strong enough to make the coil white-hot, or self-luminous. If this can be done economically, it is obvious that a marked advance has been made in artificial illumination."

"A recent article in one of our daily papers entitled 'Steam from Petroleum' has brought us a number of inquiries concerning the use of petroleum as a fuel. Upon the discovery of petroleum in America attention was at once directed to it in the hope of finding a fuel possessing important advantages over coal, and in every direction efforts were devised for its application; but its constitution and character were so little understood, and so little was known of the peculiar treatment demanded for the development of its powers as a fuel, that most of the proposed methods proved worthless. After the elimination of the majority of these methods several remained that possessed, in a greater or lesser degree, certain points of value. It has been determined, for instance, that the oil should be atomized, as it is said; that a jet of steam impinging upon a drip of the oil and conveying it into the furnace was the most effectual agent for this purpose, and that an exceedingly large amount of air was required to combine with the gases to ensure complete combustion. Further investigation, however, determined that the steam jet greatly interfered with combustion by abstracting heat from the flame, and that to be effective the steam should be superheated to so great a degree it would vaporize the oil on contact. Within the past few years such a good account has been made of this knowledge that all indications strongly point to the general substitution, in no very distant future, of petroleum for coal in the formation of steam."

"In spite of the reported discoveries of efficient means of protection against the phylloxera, that terrible insect still continues its ravages in France. In 1865 the French vineyards yielded close upon 70,000,000 hectoliters of wine, and in 1869 more than 71,000,000. Now only about 40,000,000 hectoliters can be counted upon."

"Wilson and Savage, two American missionaries, seem to have been the first, in 1846 and 1847, to bring us information about the gorilla. The skulls and skins sent by Savage have been followed up by complete skeletons and preparations sent by other travelers, and naturalists have been able thus to study the appearance and structure of the most formidable of the man-apes, which is credibly stated to inhabit central Africa from Sierra Leone in the north to Loango in the south. Living in the dense forests of that region and avoiding the presence of man, gorillas are seldom to be met with. We have no authentic portrait of a live adult gorilla. In comparing the skeleton of the adult gorilla with that of man we find that the vertebral column offers slight and unimportant differences. The number of pairs of ribs is 13; in man it is usually 12, although occasionally 13 are found. The cranium of the gorilla is very small in proportion to that of man. The contents of the smallest skull of man is given at 62 cubic inches; that of an adult gorilla is given at 34 cubic inches."

THE AUTHORS

GEROLD YONAS ("Fusion Power with Particle Beams") is manager of the fusion-research department at Sandia Laboratories in Albuquerque, N.M. He obtained his bachelor's degree in engineering physics at Cornell University and was then awarded a Guggenheim fellowship to do graduate work at the California Institute of Technology. While he was at Cal Tech he worked at the Jet Propulsion Laboratory as a senior scientist in the fluid-physics group. After receiving his Ph.D. in 1966 he went to the Physics International Company to do research on high-current particle beams. In 1972 Yonas moved to Sandia Laboratories, where he is now the leader of some 100 investigators working on the application of intense electron and ion beams to controlled fusion reactions.

P. JONATHAN G. BUTLER and AARON KLUG ("The Assembly of a Virus") are on the staff of the Medical Research Council Laboratory of Molecular Biology in Cambridge, England. Butler was educated at the University of Cambridge, where he received his Ph.D. in 1967. Since then his interests have shifted from protein chemistry to the interactions of proteins and nucleic acids, with viruses as a model system. Klug is joint head of the laboratory's division for structural studies. A native of South Africa, he received his bachelor's degree from the University of the Witwatersrand, his master's degree from the University of Cape Town and his Ph.D. from the University of Cambridge in 1952. After an additional year at Cambridge doing research on the physical biochemistry of hemoglobin he joined the crystallography laboratory in the department of physics at Birkbeck College of the University of London, where he studied virus structure in collaboration with Rosalind E. Franklin. From 1958 through 1961 he was director of the Virus Research Project at Birkbeck College, and in 1962 he moved to the Laboratory of Molecular Biology. Klug's research has centered on the development of X-ray-crystallographic and electron-microscopic techniques and their application to the structural analysis of tobacco-mosaic virus, transfer RNA, microtubules and chromatin.

EBERHARD SPILLER and RALPH FEDER ("The Optics of Long-Wavelength X Rays") are physicists on the staff of the Thomas J. Watson Research Center of the International Business Machines Corporation. A native of Germany, Spiller obtained his Ph.D. in physics from the University of Frankfurt in 1964. After four years on the faculty there he came to I.B.M. He has done research in a variety of fields, including semiconductors, laser physics, holography and integrated optics. Feder did his undergraduate work at Indiana University and then joined the staff of the Pitman Dunn Laboratory at the Frankford Arsenal in Philadelphia. He received his master's degree in physics from the University of Pennsylvania in 1953, and after an Army fellowship at the University of Birmingham he joined the staff of the Watson Research Center. He is now working on an X-ray microscope for use in the biological sciences.

BREYNE ARLENE MOSKOWITZ ("The Acquisition of Language") is associate professor of linguistics at the University of California at Los Angeles. She did her undergraduate work at the University of Pennsylvania and received her Ph.D. from the University of California at Berkeley in 1971, joining the U.C.L.A. faculty the following year. Moskowitz writes: "My primary nonprofessional interests are wilderness and photography. I do a lot of backpacking in the Sierra Nevada and the California, Arizona and Utah deserts, and I have worked as a seasonal ranger-naturalist for the National Park Service."

PAUL GORENSTEIN and WALLACE TUCKER ("Rich Clusters of Galaxies") are astrophysicists, the former an experimentalist and the latter a theorist. Gorenstein is an associate of the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory. He received his undergraduate training at Cornell University and his Ph.D. from the Massachusetts Institute of Technology in 1962. After spending a year in Italy on a Fulbright fellowship, he worked in the space-research division of American Science and Engineering, Inc., before joining the newly formed high-energy astrophysics division of the Center for Astrophysics in 1973. Gorenstein is currently involved in the development of an X-ray detector for the second orbiting high-energy astronomy observatory (*HEAO-2*). Tucker is a free-lance astrophysicist living in Fallbrook, Calif. He studied at the University of Oklahoma and the University of California at San Diego, which gave him a Ph.D. in 1966. After two years as assistant professor of space sciences at Rice University, he worked at American Science and Engineering, moving in 1971 to southern California. In addition to his research in astrophysics Tucker is a part-time teacher, writer and farmer.

LEONARD E. SAMUELS ("The Mechanisms of Abrasive Machining") is superintendent of the metallurgy division of the Materials Research Labo-

ratories of the Australian Department of Defence. A fourth-generation Australian, he was educated at Melbourne University, where he obtained his doctor of science degree in metallurgical engineering in 1958. His interest in abrasive machining began with efforts to improve methods of preparing surfaces of metals for microscopic examination, which led to the realization that it is necessary to understand how abrasive machining works and what it does to the surface of the metal. In 1976 Samuels was Battelle Visiting Professor at Ohio State University.

ARYEH ROUTTENBERG ("The Reward System of the Brain") is professor of psychology and biological sciences and director of the neurosciences program at Northwestern University. He received his bachelor's degree in psychology at McGill University, where he studied physiological psychology with Peter Milner. He then did graduate work at the University of Michigan under James Olds, earning his Ph.D. in 1965. Routtenberg writes: "Olds's intense interest in the biological significance of brain reward convinced me that these neural substrates play a key role in behavior, particularly in memory. As my interest in the anatomical basis of memory has developed I have devoted increasing effort to the study of brain proteins that may participate in memory formation."

FREDERICK J. HOOVEN ("The Wright Brothers' Flight-Control System") is professor of engineering at the Thayer School of Engineering of Dartmouth College. He studied aeronautical and mechanical engineering at the Massachusetts Institute of Technology, receiving his bachelor's degree in 1927, and then worked for the General Motors Research Laboratory and the Army Air Corps. With no jobs available in the early 1930's, he independently undertook the development of an aircraft radio direction finder, which he completed as vice-president and chief engineer of the radio-products division of the Bendix Aviation Corporation. From 1937 to 1956 he worked as an independent consultant and inventor and collaborated in the development of the first successful heart-lung machine. In 1956 he joined the Ford Motor Company as an executive engineer for advanced automobile products. On his retirement from Ford in 1967 he joined the faculty of the Thayer School. Hooven has some 40 patents on automotive suspensions and power trains, automotive and aircraft ignition, aircraft radio navigation, electronic phototypesetting and digitally controlled machinery and instrumentation. He is also the winner of the duration event in the First International Paper Airplane Competition, which was held by SCIENTIFIC AMERICAN in 1967.

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Correct time is 6:53.44 on Tuesday

Quartz Crystal Time... The LCD Alarm Chronograph gives you accuracy to ± 60 seconds a year. Quartz crystal accuracy that would have been considered sensational per month in earlier micro-electronic watches. And is still not available in models selling for as much as $500.00 to $1000.00.

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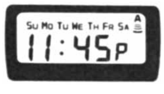
Correct date is August 8th

24 Hour Alarm

Of all the features available in digital watches today, an alarm system like this is the one that's most wanted. And no wonder. It will wake you; remind you of your appointments, phone calls and meetings (or break one up that's been going on too long). It's really important enough all by itself to warrant your getting a new watch.

You can set this alarm for any minute of any hour. Day or night. In all, 1440 positions are available—easily and instantly. Then, unless you change or deactivate it, the alarm will sound for a full minute at the same time every day. With an insistent, though pleasant, beep. When the alarm is set, an A appears on the face. To check the time it'll go off, just touch the alarm button.



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As to the chronograph, or split-second timer, it's precision is so fine, it borders on the infinitesimal. Imagine, it enables you to time an event for up to an hour to one-hundredth of a second... and beyond that, for a full 24 hours, to the second! On top of which, you can time an event in memory, keeping the regular time of display until you need the chronograph readout. Then, as you'll see in the explanation to the far right, the chronograph measures or stops time, in an extraordinary variety of ways.

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MATHEMATICAL GAMES

In which a mathematical aesthetic is applied to modern minimal art

by Martin Gardner

"Its chief merit is its Simplicity—a Simplicity so pure, so profound, in a word, so *simple*, that no other word will fitly describe it."

—LEWIS CARROLL, *The New Belfry of Christ Church, Oxford*

Modern art, particularly in the U.S., is in such a disheveled state that almost any kind of art—good or bad, traditional or avant-garde, serious or put-on—gets displayed, praised, condemned and even bought. In painting, for reasons over which critics wrangle, there is a strong movement toward realism, but in sculpture most of the movement seems to be in the opposite direction. Not that realism has not invaded the three-dimensional art world as well! Some 15 years ago George Segal started making his plaster-cast models of human figures, at first painted all white and later in bright colors. Now Duane E. Hanson has carried realistic sculpture to its ultimate by creating life-size waxworks of men and women that are the 3-space analogues of color photographs. The main trend, however, at least with respect to the outdoor sculpture found in parks and in front of buildings, has been in the abstract direction of minimal art.

Minimal sculpture is sculpture reduced to extremely simple, nonobjective forms. Junkyard art may be minimal in terms of the cost of materials, but its form is usually quite complex. A piece of driftwood art may be minimal in terms of the artist's efforts, but it also is much too complicated to be called minimal. True minimal art—the geometric shapes one now sees in public places—suggests, as Hilton Kramer of *The New York Times* has put it, "the atmosphere of the assembly line, the engineering laboratory, the drafting table and the plastics factory." To Kramer's list I should like to add: illustrations in books on mathematics, in particular books on recreational solid geometry. This month we take a look at some areas where minimal sculpture and geometrical play overlap.

Let us begin with the minimal technique that consists in cutting metal sheets, folding them and perhaps painting them. Picasso's rust-colored 50-foot work that stands in the plaza of Chicago's Civic Center is a striking example of the genre. It was first modeled as a folded cardboard cutout, but it is not really minimal because it has two pupils (although only one eye) and what seem to be two nostril holes. Picasso's *Bust of Sylvie,* standing 30 feet high on Bleecker Street in New York, is more obviously a woman's face, although it too was modeled as a cutout. Completely nonobjective realizations of the technique in many colors and varieties have been created by minimalists all over the world.

The top illustration on page 28 shows a proposal for a public monument of the same type. Study it carefully. Is it possible to construct a model of this form by taking an ordinary file card, snipping it with scissors and folding it, or is it necessary to glue it along certain edges? I do not know the origin of this marvelous new test of one's ability to think in 3-space. I first heard of it from Kim Iles, who teaches forestry at the University of British Columbia. He in turn heard it from a visiting Russian professor of forestry, who had seen it in an entrance examination for the school of architecture at the University of Leningrad.

The form has come to be called a hypercard. Magicians have learned of it and have made it the basis for a number of magic tricks. (See the article "Hypercard," by Karl Fulves, in the first issue of Fulves' new magic periodical *The Chronicles,* available through magic shops.) The hypercard is also the basis for an amusing party game. Place a large model of the card in the center of the floor. The players may view it from any angle but are not allowed to touch it. Each player is given one file card and a pair of scissors, and a prize goes to the first player who comes up with a replica of the model. It is surprising how many people decide the task is impossible.

Another popular minimal-sculpture technique consists in simply building a large model of a polyhedron. Of recent works of this type one of the best-known is *Cigarette,* a huge, twisted black polyhedral prism designed by minimalist Tony Smith of South Orange, N.J. There is a cartoon by David Levine (*New York Review of Books,* September 26, 1968) that shows the Mary of Michelangelo's *Pietà* holding on her lap the limp form of a polyhedron that looks suspiciously like Smith's *Cigarette.*

Some minimalists like to reproduce an ordinary cube, although their models are usually colored with a spray gun and tipped at an angle so that no one will suppose they are merely the pedestal of a work still to come. Many more choose to work with a number of cubes stuck together at their faces. Regular readers of this department will at once recognize such forms as polycubes. I have often thought that Piet Hein's Soma cube, which consists of six tetracubes and one tricube, would make a fascinating piece of outdoor minimal sculpture. Each month its overall polygonal shape could be altered, although the pieces would have to be locked together in some way to prevent theft. (For a further discussion of the Soma cube and other polycube puzzles see this department for September, 1972.)

A polycube consisting of eight cubes arranged in a 1-by-2-by-4 rectangular parallelepiped is known as the canonical brick. This department for February, 1976, was devoted mainly to problems about the packing of canonical bricks into boxes. As far as I know the first sculptor to use canonical bricks in a work of art was the New York minimalist Carl Andre. In 1976 the Tate Gallery in London displayed a work by Andre that consisted of 120 ordinary bricks (not quite canonical, but close to it) packed into a rectangular parallelepiped two bricks high, six wide and 10 long. The bricks had been shipped to the Tate by Andre with "directions" for their assembly. Most viewers considered the work nothing more than a "pile of bricks," and London newspapers had a field day when it was disclosed that the Tate had paid Andre $12,000 for it. John Russell of *The New York Times* defended the work for its "order, resolution and... absolute simplicity," for its "clarity of intention" and for the "frank and unambiguous way in which the materials are assembled." An Andre, said Russell, "just lies there and minds its own business."

To mathematicians, however, Andre's pile of bricks minds decidedly dull business. They can think of all kinds of ways of packing polycubes that are just as pleasing aesthetically and have the added merit of being interesting. For example, consider the three-dimensional form of the flat *Y* pentomino. The rectangle of smallest area (5 by 10) that can be packed with *Y* pentominoes is shown at the left in the middle illustration on page 28. If the pentomino is given a unit thickness, so that it becomes a solid of


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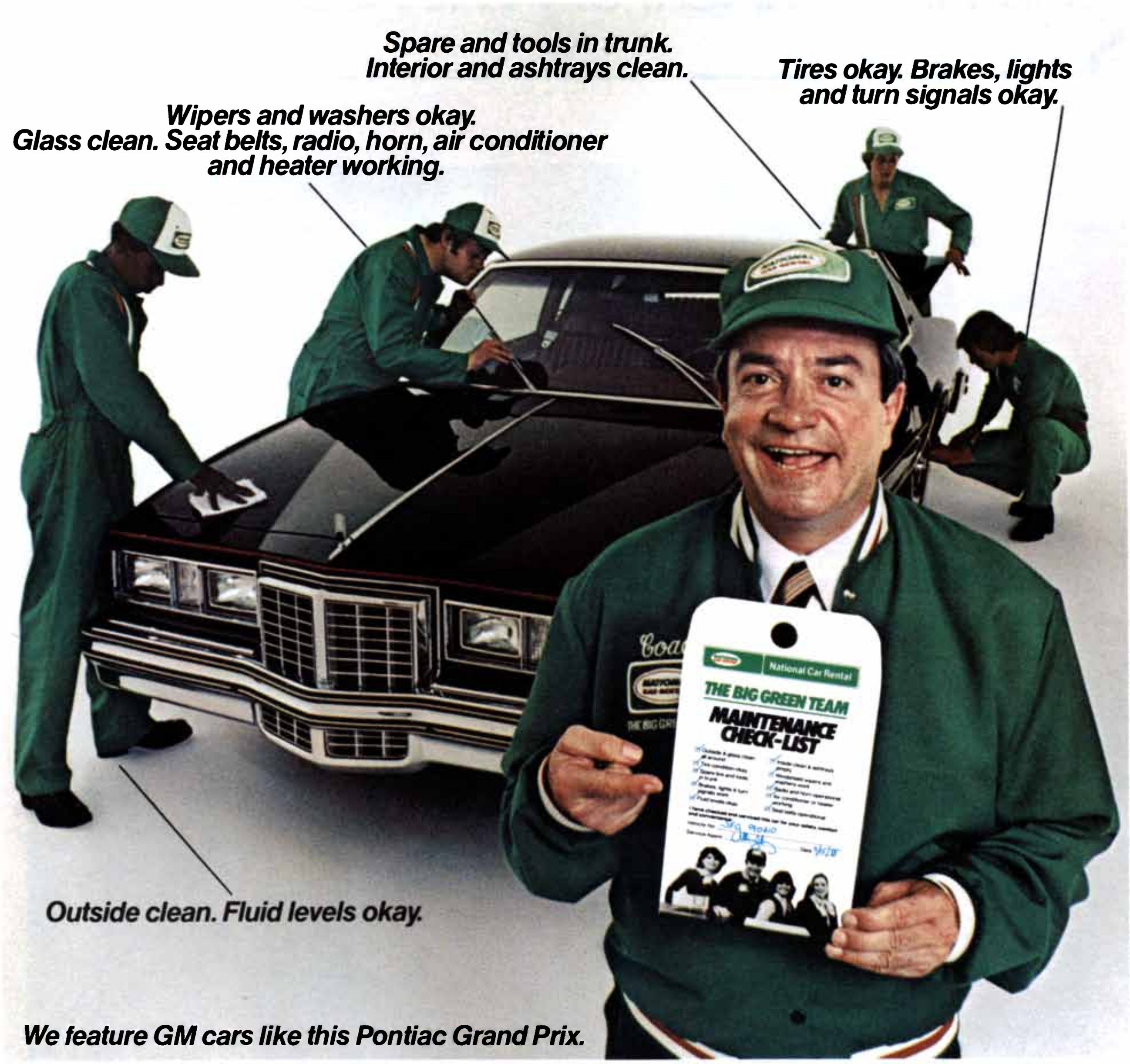

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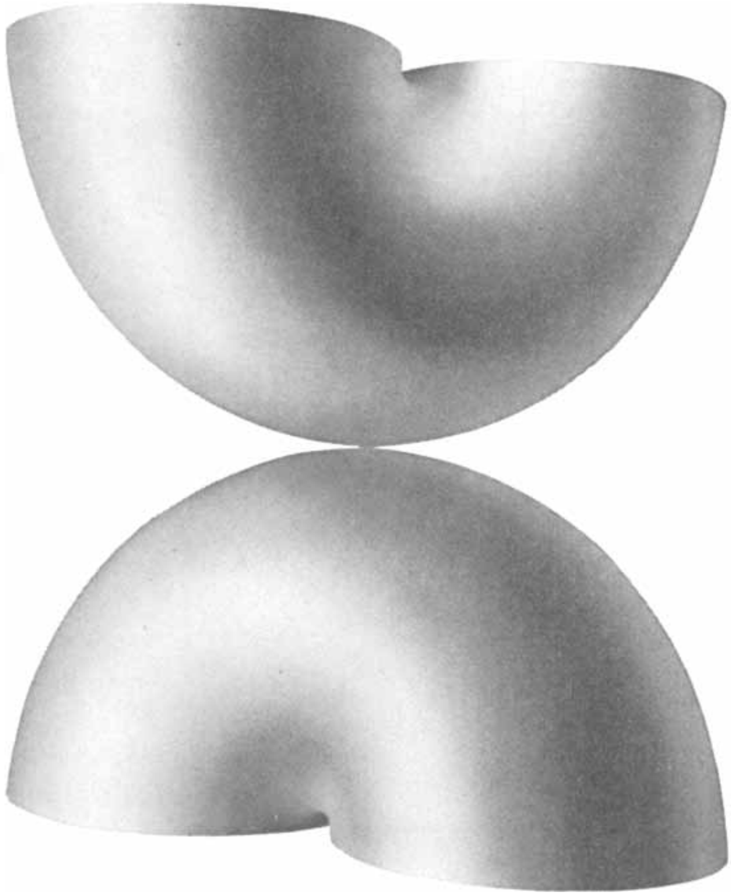
five joined cubes, it is called the *Y* pentacube. What rectangular boxes can be fully packed (without holes) using *Y* pentacubes?

To be fully packable a box must of course have a volume in unit cubes that is a multiple of 5. No fully packable box of volume 5*p* exists, where the number of *Y* pentacubes *p* is a prime. In 1970 C. J. Bouwkamp and David A. Klarner reported on the results of a computer program that found all the boxes that can be fully packed with 25 or fewer *Y* pentacubes. The smallest is the 1-by-5-by-10 box. One of its four possible packings is shown at the left in the middle illustration on the next page. There are three other boxes with the same volume, but none is packable.

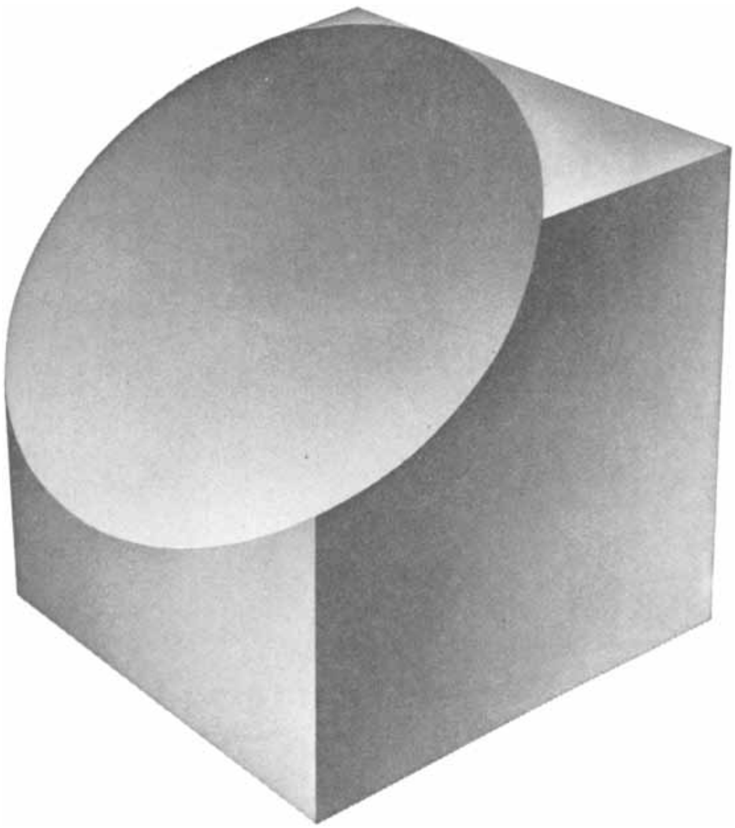
The smallest cubical box, and the only box of volume 125, that can be fully packed with *Y*'s is the 5-by-5-by-5 cube. If the reader will take the trouble to make 25 *Y* pentacubes, he will find assembling them into a cube is a splendid puzzle. The solution partly given at the right in the middle illustration on the next page is one Klarner found by hand before the computer program printed hundreds of other solutions. If Andre's Tate Gallery work had been a cube composed of 25 *Y* pentacubes instead of a rectangular parallelepiped of 120 octacubes, it would have required a more detailed set of assembly instructions, but at least it would have intrigued mathematicians.

Lewis Carroll is among those who have felt that an ordinary cube is too minimal to have much aesthetic value, and no one has been funnier in the written criticism of such art. In 1872 a new belfry was designed to house the bells that had been removed from the cathedral of Christ Church, Oxford, where Charles L. Dodgson taught mathematics. The belfry, placed over an elegant staircase leading to the hall at a corner of the Great Quadrangle, was nothing more than a simple wood cube. The design so annoyed Dodgson that he privately published a monograph on the subject titled *The New Belfry of Christ Church, Oxford*. The title is followed by a line from Keats: "A thing of beauty is a joy forever." Below the quotation Dodgson drew a picture of a square and captioned it: "East view of the new Belfry, Ch. Ch., as seen from the Meadow."

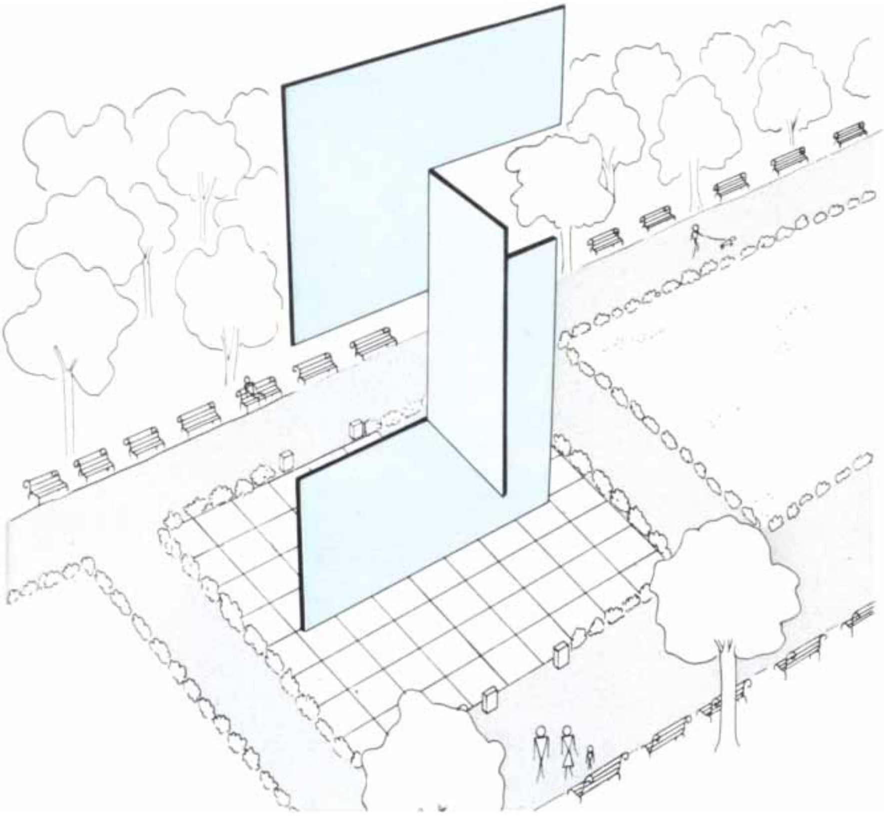
Dodgson opens his monograph with a note of etymology. The word "belfry," he writes, is from the French *bel,* meaning "beautiful, becoming, meet," and the German *frei,* meaning "free, unfettered, secure, safe." Therefore it is equivalent to "meatsafe," an object to which the belfry bears a perfect resemblance. Dodgson also speculates on why the design was chosen: Some say a chemistry student suggested it as a model of a crystal, but others affirm that a lecturer in mathematics found the design in the eleventh book of Euclid. The



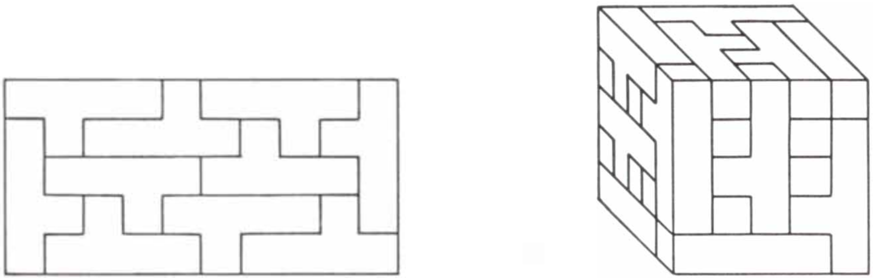
Drawing of Max Bill's **Construction from a Circular Ring**



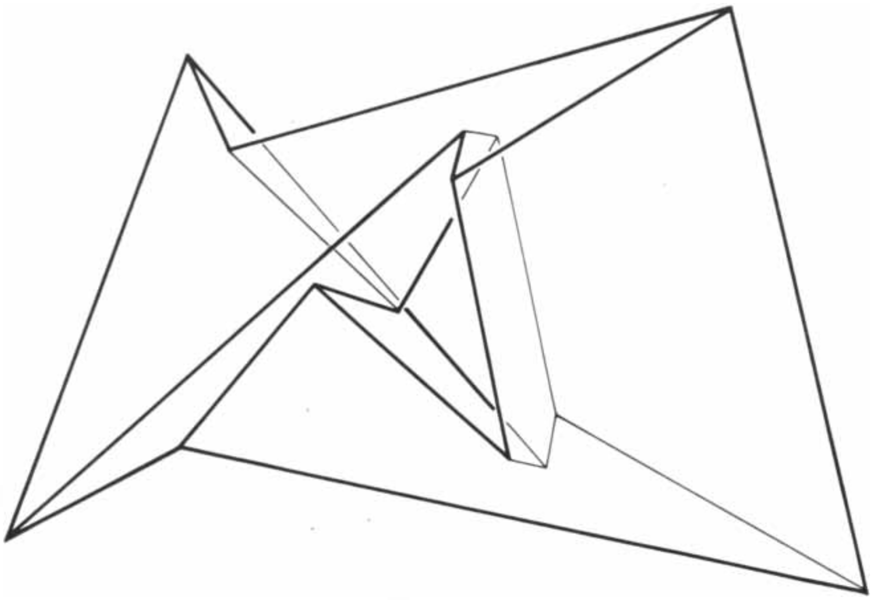
Minimal sculpture by Mitsumasa Anno



Design for a minimal-sculpture monument



Y *pentominoes* (left) *and* Y *pentacubes* (right)



The Szilassi toroidal polyhedron

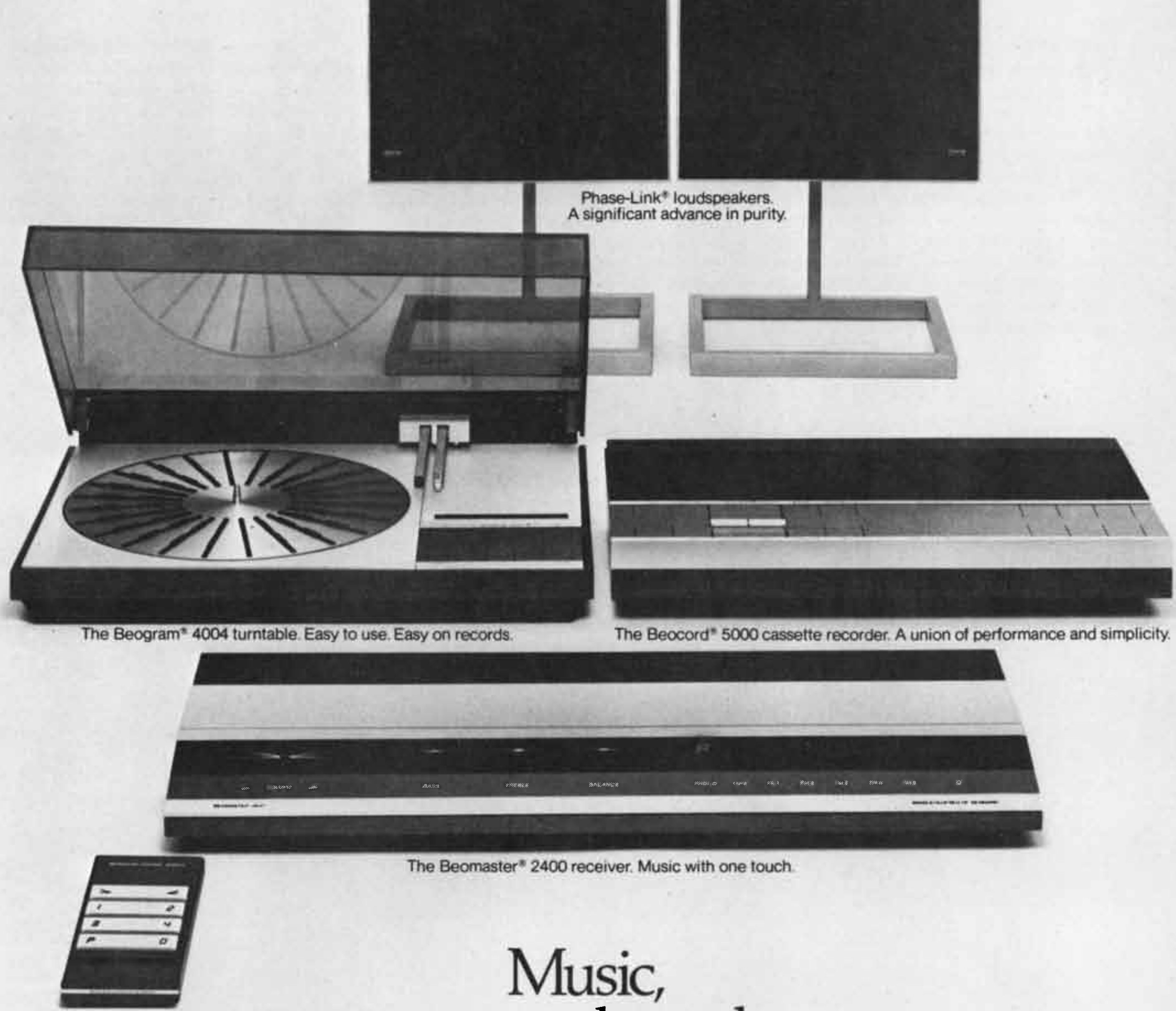
true story, says Dodgson, is that the belfry was designed by a wandering architect, now in a mental institution, who took his inspiration from a tea chest.

To get the best view of the belfry Dodgson recommends looking at it from one corner, so that one can see the edges of the cube converge in perspective on a vanishing point. This view gives rise to his happy thought: "Would that *it* were on the point of vanishing." Next one should make a slow circuit around the quadrangle, "drinking in new visions of beauty at every step," and then walk slowly away until one experiences "the delicious sensation of relief" when the belfry is no longer visible.

The belfry's stunning design, Dodgson continues, has already inspired manufacturers. Two builders of bathing machines at Ramsgate are making their machines cubical, and there is now a bar of soap "cut in the same striking and symmetrical form." He has been told that Borwick's Baking Powder and Thorley's Food for Cattle are sold in no other shape, and he proposes that at the next Gaudy Night banquet each guest be given a "portable model of the new Belfry, tastefully executed in cheese." There is much more, including syllogisms, a dramatic skit and parodies of passages from famous poems. The complete monograph, along with Dodgson's drawing of the belfry, is reprinted in the Dover paperback *Diversions and Digressions of Lewis Carroll.* An introduction explains some of the monograph's inside jokes and topical allusions.

A remarkable polyhedron that would make a work of minimal sculpture far more interesting than a cube was discovered in 1977 by Lajos Szilassi, a Hungarian mathematician. It is a seven-faced toroidal polyhedron, that is, all its faces are polygons and it is topologically equivalent to a doughnut. It shares with the tetrahedron the extraordinary property that every pair of faces have an edge in common. Until Szilassi's computer program found the structure it was not known that it could exist.

In this department for May, 1975, I described a 14-faced polyhedron that was discovered in the late 1940's by another Hungarian, Ákos Császár. The Császár and Szilassi polyhedrons are closely related. The Császár polyhedron is also a toroid, and it shares with the tetrahedron the property of having no diagonals. The Szilassi polyhedron is the topological dual of the Császár polyhedron: the two have the same number of edges (21), but in the Szilassi polyhedron the 14 faces of the Császár polyhedron have been replaced by 14 vertexes and the seven vertexes of the Császár polyhedron have been replaced by seven faces. The bottom illustration at the left shows what the Szilassi polyhedron looks like. Note that the hole is unusually large and that there are three pairs of congruent faces. For readers



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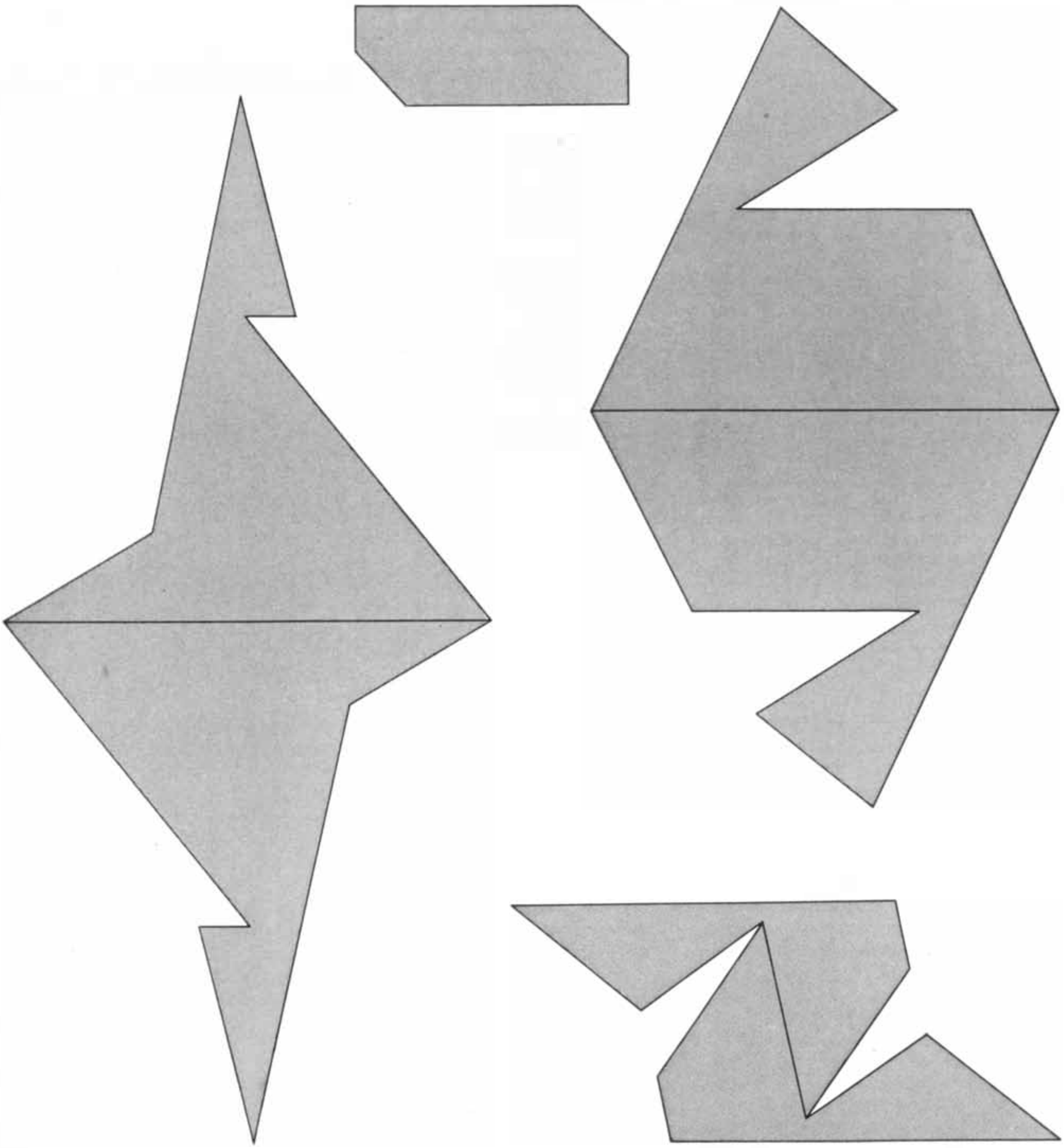
who wish to make a model of the Szilassi polyhedron E. N. Gilbert of Bell Laboratories has provided the patterns for all seven faces shown in the illustration below. Each pair of congruent faces can be cut as a single piece and folded along their common edge.

The most delightful aspect of the Szilassi polyhedron is that it shows how a seven-color map can be drawn on a torus, that is, a map that must be colored with seven colors so that no two adjacent regions are the same color. On the plane or on a solid topologically equivalent to a sphere the largest number of regions that can be mutually adjacent is four, a fact displayed by the four faces of a tetrahedron. On the torus the corresponding chromatic number is seven. Color each face of the Szilassi toroid a different color and then imagine the toroid inflated to the shape of a doughnut. The surface will be covered with a seven-region map requiring seven colors.

Minimal sculpture is not, of course, limited to polyhedrons. Constantin Brancusi's *Bird in Space* is a well-known early example of free-form minimal sculpture. Many other sculptors have created simple structures with curved lines that have mathematically interesting properties. Eero Saarinen's mammoth Gateway Arch, which dominates the skyline of St. Louis, comes at once to mind. It has the form of an inverted catenary, the curve assumed by a chain when it is held at the ends and allowed to hang in a loop.

For the past 40 years no artist has been more influenced by mathematical concepts than the Swiss artist Max Bill, as is shown by his hard-edge painting



Patterns for the faces of the Szilassi polyhedron

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and minimal sculpture. Bill's fascination with topology is reflected in dozens of works featuring curved surfaces that like the Möbius strip are one-sided. Many of his constructions are strange but oddly pleasing dissections of a simple solid, such as a torus, a sphere or a cube, into two congruent parts. For example, in the work shown in the top illustration on page 27 Bill cut a black diorite torus in half and then balanced one part on the other.

Bill also executed a series of five works, each of which is based on a different way of cutting a sphere into two identical parts. Bill may not have been aware of it, but one of the works, the gray granite *Half Sphere around Two Axes,* is based on an old folk method of quickly slicing an apple into congruent halves. A half sphere cut by this method is shown in the illustration below. It is not as easy to make as it looks. Make a vertical cut halfway through the center of the top of a sphere. Turn the sphere over and make a second halfway cut, perpendicular to the first, through the center of the bottom of the sphere. Now make two horizontal cuts through diagonally opposite quarter sectors of the sphere's equatorial disk. The half sphere shown in the illustration is one of the two identical halves that result. Note how it suggests a three-dimensional version of the yin-yang bisection of a circle into asymmetric, congruent parts.

I close with a truly wondrous example of minimal sculpture designed by Mitsumasa Anno, a Japanese graphic artist. The bottom illustration on page 27 shows a work from his latest book, *Anno 1968–1977.* A huge marble version of this mysteriously truncated cube would make an appropriate monument for the sunny grounds of California's Stanford Research Institute. It would symbolize the management's faith in the military applications of the continuing research on clairvoyance by their two most famous paraphysicists, Harold Puthoff and Russell Targ.

Here are the answers to last month's problems about Egyptian fractions:

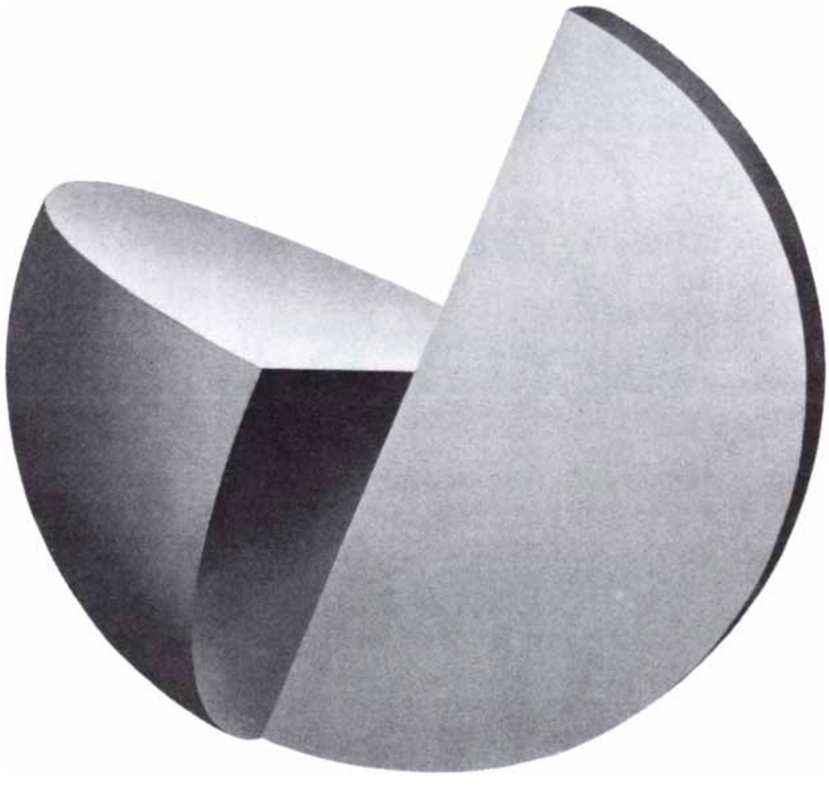
1. The only solution is the expansion $1 = 1/2 + 1/3 + 1/6$.

2. The expansion is $67/120 = 1/3 + 1/8 + 1/10$.

3. The expansion is $8/11 = 1/2 + 1/5 + 1/37 + 1/4{,}070$.

4. The smallest value for b is 5. The greedy algorithm gives the expansion $3/5 = 1/9 + 1/113 + 1/25{,}425$, but there is also the expansion $3/25 = 1/10 + 1/50$.

Last month I gave 1976 as the date of the discovery of the five ways of expanding 1 to a sum of nine Egyptian fractions with odd denominators. Sin Hitotumatu, who translates this department for the Japanese edition of SCIENTIFIC AMERICAN, sent me a 1971 paper that gives the five expansions. These earlier results are the work of S. Yamashita, one of Japan's most skillful computer programmers.



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BOOKS

The history of salt, the rise of the "chip" and how the Indians lost faith in their game

by Philip Morrison

NEPTUNE'S GIFT: A HISTORY OF COMMON SALT, by Robert P. Multhauf. The Johns Hopkins University Press ($22.50). Not so much the pawning of the gleaming gems of Isabella as the annual harvest of coarse crystals of sea salt is likely to have financed the voyages of Columbus. There is a shallow lake on the White Coast of Spain, not far from Alicante, that fills with seawater in the winter storms and dries in summer to "a mass of salt." Its wealthy owners invested in the daring venture onto the Ocean Sea (to reciprocate in some way that gift of Neptune?).

The sea around us is the ultimate source of all common salt, immediately or after a long delay. Humanity has always demanded its salt. Blood, sweat and tears are salty, but of course so is the food we eat. Tradition and experience suggest, if direct data do not yet confirm, the view that herbivores and agricultural man, but not carnivores and hunters, need added salt. A universal craving for salt is undeniable, "perhaps as the primordial narcotic." The buffalo tracks to the salt licks were virtual roadways. The Anasazi mined rock salt in Arizona 1,000 years ago, and the Neolithic salt miners of Hallstatt were already flooded out by the La Tène period. The Chinese have taken brine from deep-drilled wells in Szechwan since the Han period or before. We Americans still carry about five kilograms per head of the white crystals home each year from the supermarket. We use as much again in salting fish and meat for the table, and about the same amount is offered to our livestock, mixed with their feed or as delicious blocks to lick. That totals about four and a half million tons, a substantial trade, the modern survival of an ancient worldwide industry offering revenues to the state and engaging many workers over the entire history of society.

But salt is not to be understood by the culinary needs that are so patent and so romantically ancient. In about 1850 the world of salt began its transformation, by now complete, into the chief nonfuel material of the chemical industry, after air and water. *Neptune's Gift,* written by a reflective and learned historian of chemistry, documents the entire story, one of "unlimited demand, inexhaustible supply," a tale with plainly cautionary implications.

For every pound of salt for the table and the feedlot we spread nearly two pounds on icy roads. These are all uses for salt solution, with both of the two ions of the compound about equally important. The older industry had long found important requirements for the sodium alone, needed in soap and glass and derived from soda ash (sodium carbonate). This works in our time too, at the rate of about 20 pounds per head per year. Much soda is now recovered from deep-lying natural layers of the stuff in Wyoming. An order of magnitude above all that, we use a couple of hundred pounds per head per year in the separate atoms of the salt, as chlorine and as sodium hydroxide. The chlorine is indispensable for plastics (observe that vinyl chloride is also named monochloroethylene), solvents, the Freons, pesticides and bleaches, the last mainly for wrapping papers. (Water treatment uses only a few percent.) The partner sodium ion, released with the chlorine in the electrolysis of brine, provides by its interaction with water the alkaline regime needed in the aluminum, rayon and phenolic-plastics industries. Neither sodium nor chlorine itself enters those products.

The economic picture of salt, albeit substantial and interesting, is to some degree a reflection of intention rather than of reality. Dr. Multhauf is careful and explicit with it, offering detailed "conjectural" accounts of the uses of salt in four countries for 1900, for the U.S. over the decades since then, and a big statistical summary for a dozen countries and scores of regions of importance. But the technology and sites of salt-winning are the soul of the book and fill its many period illustrations.

Sea salt is of course quasi-infinite on the human scale. The acquisition of salt is centrally an energy problem, governed by the costs of transport and the penalties of dilution levied by the second law of thermodynamics. When coastal peoples wanted a little salt, it was good enough to pour seawater on the embers. Next came the boiling of seawater in shallow dishes, marked to this day by prehistoric deposits of ceramic fragments at a multitude of European sites, some inland where brine springs are found. The sunnier lands relied on solar energy, and hardworking Japan depended until recent times on leaching beach sands in a special pond-and-bank arrangement, at the cost of much hand sprinkling and scraping, and finally of boiling the concentrate with charcoal. Rock salt is ancient and widespread, but the pioneers of geological science in western Europe had forgotten it, immersed as they were in the contemporaneous industry of seawater and brines. The Carpathians were far away, and the deep and ancient salt mines near Cracow astonished the early Royal Society.

England's salines (around Cheshire and Droitwich, say) were based on shallow inland brine pits and lent themselves to a strong export trade in the 17th century and even later. Ports were close, ships in the wool trade needed ballast, and coal was exploited early by the English brine boilers. The value of concentration beyond that of seawater is of course not the need for salt content but the saving in fuel; in most circumstances the fuel burned outweighs the salt shipped by quite a factor. Even the dark solar salt of the French Atlantic coast gave way to the English product. The Continent struggled for inland salt sources and for stronger brines. By 1750 we read of saving fuel by the recirculating of evaporation in long buildings with walls of straw or blackthorn, as much as a kilometer long and provided with controls for changing brine flow to adjust for shifts in the wind. That carefully managed surface was an early cooling tower on a grand scale, saving two-thirds or more of the wood burned in boiling. (Photographs show one such structure as it stands today in Poland, an inland resort that offers seashore air.)

At its climax this phase merged into the rise of industry. The Bavarian brines around Reichenhall had been worked for a couple of centuries to provide salt without need for import, in peace and in war. By about 1820 these works had brine canals scores of kilometers long crossing the mountains, with lifts of hundreds of meters, delivering 1,000 tons of salt per day. These formidable schemes relied on special water-column pumps, a kind of piston engine worked by flowing water under high head, used instead of water wheels. On December 16, 1817, the Ilsank brine pump was put in operation, at some 50 horsepower "the largest machine in the world." Although a competitor had scorned them as the work of a "mathematischen Experimentenmacher," some of these tall cast-iron engines remained in service for more than a century.

The change came at both ends: demand and supply. Soap and glass became commonplace as the soda works appeared. At the same time geologists came to understand the past, and practical men learned deep drilling. The Szechwan pioneers working with bamboo pipes and a tapelike "cable" became known to the scholars of Europe early in the 19th century. By then the German salt specialists and those at Kanawha in West Virginia were finding salt by drilling down hundreds of meters. The tricks of deep drilling were remarkably similar all over, probably by convergence rather than transfer. The first borehole to go down a kilometer was finished in 1871.

The salt of old seas is now known at depth over much of central Europe and widely in North America, particularly on the Gulf Coast. Salt domes offer a plentiful supply, taken up as brine by sending down fresh water, as the miners had learned to do in the ancient works once some mishap had flooded the salt seam. The mixture of crystals that is the hallmark of sea salt, the curious natural separations and enrichments (of potash, of other sodium salts, such as Epsom and Glauber's, and here and there even of borax and lithium) became rationalized and exploited as the chemist, the geologist and the mapper-driller worked together.

SALT IS MADE FROM SEAWATER in this woodcut from Georgius Agricola's *De re metallica* of 1543. *A* is the sea, *B* a pool, *C* a gate, *D* trenches, *E* salt basins, *F* a rake and *G* shovels.

This volume is a source of much knowledge and an impetus to questions about the mutual rise of science and technology, their differences country by country and period by period, and about the hard issues of externalities and of overdevelopment. Dr. Multhauf writes well, with reflection and a lively, skeptical touch. He is so careful about the old area units for French salt pans, say, that a reader may wonder about the lack of a few pages devoted to material and energy balances for the various salt technologies described. That absence leaves one with a sense of incompleteness: the fuel needs of the past are visible only in glimpses, and the scale and nature of the end-product wastes of today and yesterday are hard to understand.

Young Matthias Schleiden, "a romantic German naturalist," was the codiscoverer of the biological cell in 1838. In the 1870's he announced his intention of writing "complete" histories of an animal (the horse), a plant (the rose) and a mineral (salt), spanning knowledge from folklore to science. He thereby sought in his time to bring science and technology to all the literate. But in 1978 any book on salt, says the author of this one, "like the time when it was written, is dominated by science and technology." That tale alone is full of wonder, even if here ethnography and folklore have been sacrificed for a wider sweep of economics and engineering. Scale and change have seized us, and our interwoven knowledge rests on a scaffolding "no more fragile perhaps than that of Schleiden's time, but certainly far higher. There is farther to fall."

REVOLUTION IN MINIATURE: THE HISTORY AND IMPACT OF SEMICONDUCTOR ELECTRONICS, by Ernest Braun and Stuart MacDonald. Cambridge University Press ($16.95). By 1953 Project Tinkertoy had spent $5 million, only to be shut down. Its aim had been to provide the Navy with mass-produced miniature electronics. Ceramic wafers about an inch square were imprinted with circuit leads that interconnected the various little components. Riser wires led to similar wafers mounted above, and on top of the stack of wafers sat a subminiature vacuum tube, the size of a big thimble. Tinkertoy worked; it neatly assembled circuitry in a way that fitted the custom-

ary view of compactness among human artifacts. Indeed, it promised to pack eight or 10 parts per cubic inch in quantity, a factor of 2 better than the best earlier efforts at miniaturization.

But even Tom Thumb would be too clumsy to assemble the modern large-scale integrated circuit; its half-million elements per cubic inch are quasi-biological and no kin to the work of the deftest craftsmen of the past. In peace or war this new technology is sure to change our lives forever. The point is not, of course, that familiar tasks can be carried out by hand-held devices where a roomful was once needed; rather, it is that all kinds of cheap but clever machinery will come to perform novel tasks with a silicon surrogate for the brain and the eye.

There was a prophet. In 1952 transistors were seen as low-power capsule-size substitutes for individual amplifier tubes, already a small-scale success even as Tinkertoy was setting up its assembly line for tubes on wafers. The U.S. military bought nearly every one of the 90,000 transistors made in 1952, most of them tweezer-assembled point-contact devices, the fruit of a profound solid-state physics (although realized through the mechanical analogue of the galena crystal and cat's whisker of 1920). In Washington that year a visitor from the Royal Radar Establishment, G. W. A. Dummer, prophesied in public the next logical step: "[Electronic] equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected directly by cutting out areas of the various layers." His was a fair description of a modern chip, now realized in fingernail size by the 10 million, at a dollar or two each.

Dummer "carried inspiration around on his back like pollen," one observer remarked. But no one yet knew how to make what he foresaw. The Royal Radar Establishment, working with some British companies, went ahead indecisively for a while. Then in 1959 the first integrated-circuit patent was filed by Jack Kilby of Texas Instruments, who was quite ignorant of Dummer's vision. Kilby had been with Tinkertoy, and in Texas he worked up a design for separate components interconnected by hand within one chip of germanium. Meanwhile Robert Noyes at Fairchild had found the way to batch transistor production: "We had, because of the particular way we had decided to make transistors by leaving an oxide layer on top of them, one more element than everybody else,... and that happened to be the one that worked." It was this planar technique that was the key. It dealt with a flat surface easily worked by photoresist methods, embodying carefully

DUPLICATION TECHNOLOGY

Unfair Copy

The watch shown here is a copy of the world famous Seiko chronograph alarm. Unfair? You be the judge.

All the features of the Seiko watch are duplicated in this digital watch. It is an excellent example of the fierce competition in the United States.

It's really a shame. The watch shown above is a copy of the Seiko chronograph alarm.

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The Seiko chronograph alarm sells for $300. The watch costs jewelers $150. And jewelers love the item, not only because of the excellent reputation of the Seiko brand, but because it's probably America's best-selling new expensive digital watch. And Seiko can't supply enough of them to their dealers.

The Mercury copy shown above looks almost exactly like the Seiko and costs dealers approximately $50. Most dealers are selling it for $100, and they're selling them as fast as they get them.

LABOR EXPENSIVE IN JAPAN

Unlike the Seiko watch which is made in Japan, the Mercury is manufactured under special contract in Hong Kong by a prominent American watch manufacturer. The watch uses basically the same components as the Seiko, but the differences lie mainly in the labor. Hong Kong's labor costs are far less than in Japan. An average Japanese watch assembler makes the equivalent of $75 per day whereas the equivalent employee in Hong Kong makes only a few dollars per day.

The value of the yen has skyrocketed while the Hong Kong dollar has changed little in comparison to the U.S. dollar. So all Seiko products have become even more expensive to export.

BOTH BACKED BY SERVICE

The Seiko is backed by a national network of service centers. The Mercury is backed by a very efficient service-by-mail center. Since the latest crop of space-age digital LC watches require very little service other than battery replacement, which any jeweler can do, service has become less a concern.

Why then would anyone want to buy a copy of the Seiko? For several reasons:

Savings JS&A has obtained sufficient quantities of the Mercury to offer you the item for as low as $69.95.

Support Mercury is a division of Leisurecraft Industries, a public company that specializes in obtaining the best digital watches and insuring their value with excellent service, support and quality.

Quality You'll be amazed at the excellent quality of the Mercury, especially compared side by side with the Seiko.

Accuracy The Mercury is guaranteed accurate to within 15 seconds per month, although much greater accuracy can be expected.

THE BEST FEATURES

The alarm chronograph has an alarm that really wakes you up. Its chronograph measures time to one hundredth of a second and has three settings: **split** which continues counting the split seconds while you freeze the time for reading, **add** if you want the total time of several periods, and **lap** which starts counting from zero when you press the button.

You have hours, minutes, seconds, day of the week, the month and date. The Mercury Quartz LC also remembers the days in a month and automatically recycles to the correct first day of the next month.

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doped oxide passive layers and metal connections. The need for both metal and oxide layers called for silicon. No step of this was in itself new: Bell Laboratories had developed the basic procedures. It was the whole that was new.

The transistor was the conscious result of a powerful physics, backed by a prehistory of solid-state devices. The legacy of that success was a scientific style of industrial development, seeking to wring a series of basically new devices out of the physics of the semiconductor. The planar technique was different. It was clearly process technology, motivated by the need to make "what was in some ways an inferior transistor reliably and cheaply." The modest commercial effort found hidden treasure: a prodigal combinatorial richness, "the power of process over product which has determined so much of the course of semiconductor electronics."

Thus do the two English authors, a physicist and a historian from the University of Aston in Birmingham, document a watershed in the growth of the silicon world. They begin with Genesis, when Karl Ferdinand Braun of Marburg found the rectifying cat's whisker, and spin the story through the war and Bell Labs to the transistor industry, the rise of Silicon Valley and the spread of the arcane art somewhat fitfully to Europe and Japan. A little apart from the theater of battle, far from Palo Alto as they are, they rather naturally bring detachment. They gain their perceptions not only from a flood of publications but also from interviews with many participants in the events they chronicle. (Indeed, the only fault a reader is likely to find in this brief and timely book is inadequate identification of the people who supply the comments the authors enjoy quoting.) Silicon is abundant, and the energy consumption of the industry is small. Its externalities are few. "We have irrevocably entered the electronic age, and it is up to us to make it a good age in which to live." They end so, without saying how.

The future is quite likely to regard our times as a kind of second coming of old Gutenberg. The incunables of this new infant were the discrete components, and in the 1960's that cradle was outgrown. A new model of chip is less like a new invention than it is like a new book, its logical architecture and the economy and elegance of its expression giving it value. New components are like new fonts, which gain widespread use only relatively rarely. This careful, professional but rather personal account is the most satisfying story yet seen of the shops, the journeymen and the masters who print the tiny Boolean texts.

KEEPERS OF THE GAME: INDIAN-ANIMAL RELATIONSHIPS AND THE FUR TRADE, by Calvin Martin. University of California Press ($10.95). In the cosmology of the hunting peoples of eastern Canada, say the Cree, the Ojibwa and the Micmac, each species of game was ruled by a spiritual keeper, or "boss," often personified. Once in a great while a lonely hunter would catch a glimpse of the giant white beaver that ruled over beaverkind and apportioned their life and death at the hands of the hunter, in accordance with the harmonies of the world. The hunters held their necessary quarry in conscious respect: overhunting was regulated, season by season, by a subtle network of custom, belief and sign that was often mediated by the visions of the shaman. "To kill too many game was to risk the ire of the game bosses." Clearly such a system was adaptive for a folk too far north to gain much from the culture of staple maize.

How then was that harmony untuned? How did it come about that once the fur trade offered European goods for pelts Indians sought out the fur trader with the avidity of the bazaar? When in 1534 Jacques Cartier first met the Micmac, those hunters literally mobbed his party, insisting that he trade with them for furs. He had to fire a volley over their heads to "dampen their ardor." Do we suddenly see acquisitive economic man there in the hunters, the very folk who had lived, free of many wants for goods, working only modest hours at the hunt, for thousands of years in equilibrium with their prey?

Professor Martin, a young Rutgers historian, gives another answer. This is a tale of Europeans and Indians and three other species (a virus, a fish and a rodent) in close and curious interaction. Five or 10 millenniums back the first smallpox virus came to some Asian villagers who, it may be, had newly mastered the domestication of cattle. A virulent recombinant or mutant of some mild cattle disease, it has forever after dwelt ominously among exposed human beings, wherever their settlements have been large enough. Europe became host to the virus at the time of Classical Greece, or even later.

The people of the Americas had left the Old World before ever smallpox arose. They remained unexposed, virgin soil for its attack. Now, decades before settlers or even the voyageurs had penetrated the American forests and streams, the ships had come from Bristol and Lisbon to fish the generous banks for cod. Each summer, as early as the 1480's, some fishermen had gone ashore in Newfoundland or Nova Scotia to dry their catch, and some had made contact with the aboriginals. Archaeology offers in evidence sailor's goods, not trade beads or knives but belaying pins, seamen's earrings and the like, dated up to 1550 or so. Great epidemics then decimated the Indian and ran their course even far to the west, smallpox often reaching some Indian groups before they had seen Europeans or heard the sound of gunfire. Men and women died in pitiable numbers; perhaps an epizootic even took the game itself.

The times were out of joint; the great compact with the keepers of the game was broken. Perhaps, as one old Cree said of another time in the 1780's, the Great Spirit became angry with the beaver and "they are now all to be destroyed." Once the Indians were fully armed with European technology they engaged in a senseless slaughter of the animals, alarming travelers of the 18th century. What had alienated man from the keepers of the game was Old World diseases; the Indians had lost faith in the "traditional avenues of spiritual redress." The animals were seen to have broken faith too, and now there was a state of war, exacerbated by the goods that flowed from the killing by way of the traders.

The ethnohistorian applies his method succinctly to four broader issues around the relation of the Indian to the game animals: the alleged Paleo-Indian overkill of the big mammals, the near-end of the beaver under the fur trade, the reduction of the endless herds of bison on the Great Plains, the practice of forest burning. In each of these plausible cases have been made for the Indians' indifference to the future of their game. Here Martin infers a "Not guilty" or at least a "Not proven." It was no one-sided ethical relationship those people had with their land, no condescending self-restraint. Rather, "Nature, for virtually all North American Indians, was sensate, animate and capable of aggressive behavior toward mankind." What was involved was nothing less than mutual respect, a reciprocal recognition of needs.

No doubt all this subtle seeking for cause in old texts is less than conclusive; cause and correlation are hard to separate whenever unique events are examined. The clarity, directness and originality of this small book should nonetheless earn it many readers, who will wonder at the tangled web of the living world and the variousness of the human mind.

The absence of author entries from the index is a solecism of the publisher that is costly for serious readers.

THE ECOLOGY OF FOSSILS: AN ILLUSTRATED GUIDE, edited by W. S. McKerrow. The MIT Press ($22.50). Imagine a learned naturalist, an English or perhaps a continental traveler, strolling along the tidal flats and beaches of Britain. He is certainly a lowlands man. Now and then he wanders to brackish marshes not far from the shore, or even to an inland lake and forest swamp, but not for him the dry moorlands or

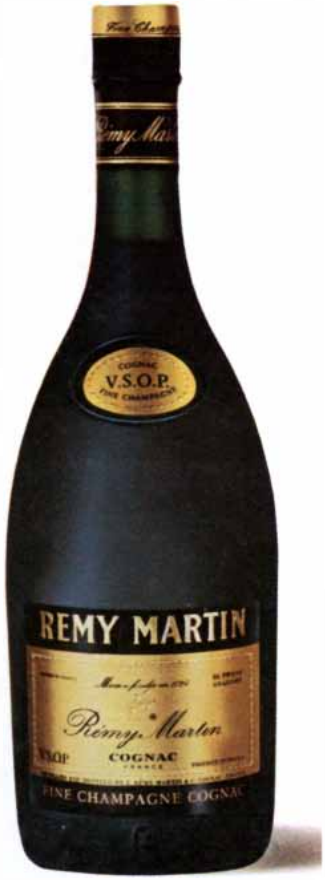
Symbols of the world's most precious elements

[1]Au

[2]Ag

[3]Pt

[4]Rm



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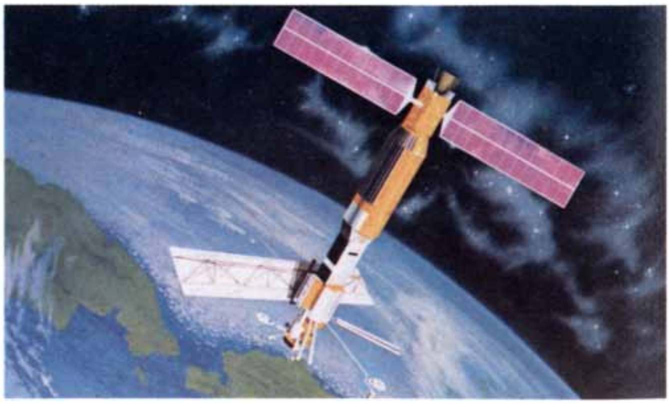

Seasat-A, an ocean-survey satellite developed jointly by NASA and Lockheed, has now gone on sea watch.

work for man.

The NASA Space Shuttle. Lockheed serves it with a wide range of technical support activities in addition to the heat insulation described below.

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Will a Seasat system pay? An in-depth study says it will be of major economic value to the nation.

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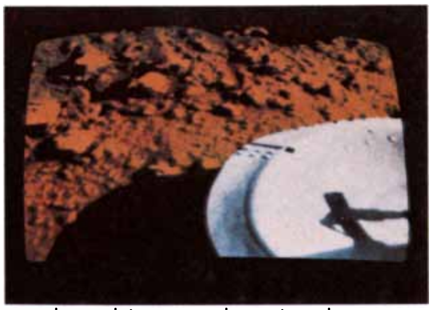

We've now put 'eyes' on Mars, viewed Venus close up, and will get intimate looks at Jupiter and Saturn in the immediate years to come.

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THAT'S IMAGINATION. THAT'S PLYMOUTH.

a rocky peak. Everywhere he goes he sketches thoughtfully, representing the typical plants and animals he finds as though they were concentrated in a cubic yard or so. His carefully scaled line drawings are reproduced in this book with a keyed list of the forms shown and a text page or two, explaining, for example, how soft ooze favors the half-buried sponge and hard surfaces are encrusted with a variety of smaller forms. From time to time he dons an aqualung to examine the shallow sea, observing the sluggish flounder or the swift whiting. Reeds and snails and strange nautiloids attract his pen and are entered on the list.

These pages hold 125 distinct sections of just that kind. Even more wonderful, our guide is an immortal. His studies span not a few seasons of travel but half a billion years. Time has enriched his count of specimens in each little cut; preservation has favored the low-lying wet world. The dozen chapters offer grouped descriptions of typical communities appropriate to some formation in those parts, geological epoch by epoch, from four locales in the Cambrian up to five of the present day. (To be sure, the modern scenes include a pair of tropical settings for which you would need to leave today's Europe, one among marine grasses, one on a coral reef.)

Our guide with the long view includes maps for us, showing the oceans in time as they open and close, the drifting land masses in their proper place. It takes 30 drawings before we reach the first of the nonmarine scenes, a freshwater pool with crayfishlike scavenging eurypterids and ancient jawless fishes "like large armored tadpoles." The first land plants enter the next scene, rootless and leafless vascular upright stems from the famous cherts of Rhynie in Scotland. The first animals seen on dry land are the great dragonflies of the Coal Measures soaring on wings with a span of almost two feet amid the high horsetails. The earliest land vertebrates in the volume are a few impressive dinosaurs resting on the shores of a lagoon in the low Triassic desert world with marine incursions, perhaps like the Persian Gulf climates of today, that covered England and the North Sea. A very modern—but oh, how conservative!—brachiopod, *Lingula*, is seen here, not much unlike its cousin *Lingulella* depicted in the first of the drawings, the one for the lowest Cambrian. Only a couple of trilobites then kept it company on the shallow, quiet flats. Trilobites are seen no more after the Carboniferous.

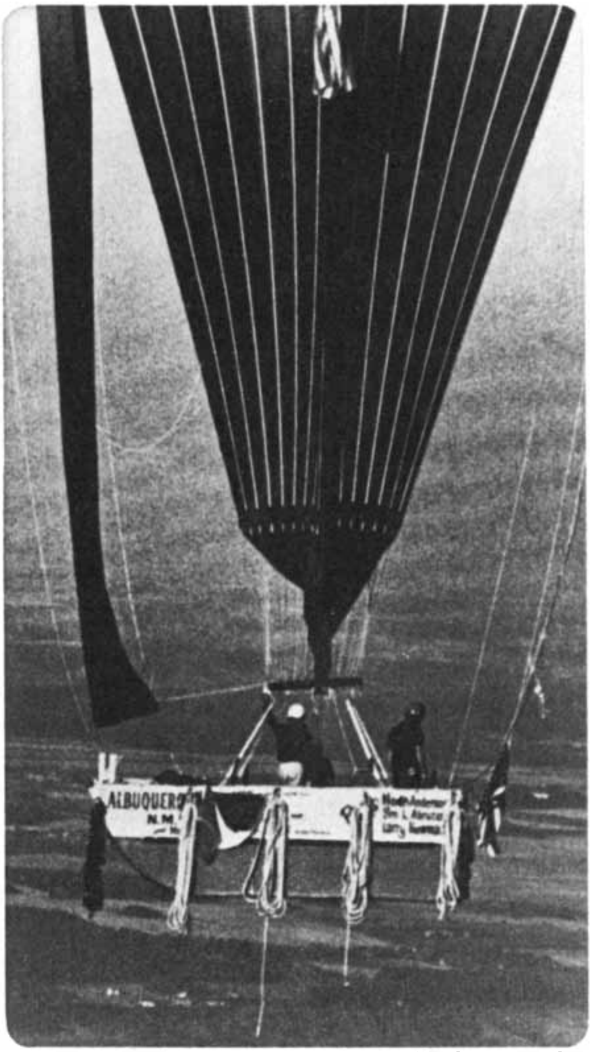
With each section is shown a shelving layer on which are drawn a selection of the fossils as they now appear, from the study of which the drawings of the living forms have been reconstructed. About 1,000 representative species have been pictured, each in its community with definite geological provenance; in many instances the same or closely similar forms will be found in most parts of the world. Seven experts divide the task among themselves by long periods; the editor is a distinguished paleontologist at Oxford. There is a valuable introduction to the principles of paleoecology, with a classification scheme for plants and animals (without the kingdom of the Fungi, rarely fossilized). The reconstructions were drawn by Elizabeth Winson and the many maps by Peter Deussen, all simply and effectively. This book is not meant as a treatise for the taxonomist, as a complete fossil key or as a guide; rather, "its main purpose is to educate and stimulate." It is an unusual success on those terms.

ATLAS OF RADIOLOGIC ANATOMY, by Lothar Wicke, with the assistance of Wilhelm Firbas and Roland Schmiedl. Urban & Schwarzenberg, 7 East Redwood Street, Baltimore, Md. 21202 ($15). Like paintings on bark by some visionary shaman of the Australian desert, these sharply detailed pictures show the bones under the skin, the coursing blood and the hidden entrails made visible in eloquent shadow. They are of course X-ray plates, printed as positives and electronically contrast-enhanced to bring out fine detail. The body is shown literally from top to toe and viewed quite broadly, with the intention of including "all common roentgen examinations." All the work was done by the staff of the Institute of Anatomy at the University of Vienna, where there is a long tradition of "anatomic-radiologic correlation." Intended for medical students, the atlas has a much wider visual appeal, particularly because the reproductions are positives, so that the more opaque bones (and the heavy-metal fillings of the teeth) stand out in black. All but one of the prints were made from living subjects; the plates have been kept free of any notations or marking lines, and a careful line drawing naming and explaining the structures shown appears on each facing page.

The book ends with a picture of beginnings: the fetal head held safe within the pelvic girdle, the delicate second spinal column rising beside the sturdy vertebrae of the mother. The well-formed bearings of shoulder, hip and knee, the arterial network of hand and foot, the bronchial tree, the intricate colon and airy lung and sinus cavities provide notable plates. The nomenclature is fully medical, although English equivalents are given for all the Latin terms. A brief glossary defining the special procedures (splenoportogram, phlebogram) would have been welcome, but any medical dictionary will unlock more meaning behind this striking and comprehensive display.

HP measurement and computer advances

When you set out on a journey without equal, you rely on a calculator without "equal."



United Press International Photo

American balloonists aboard Double Eagle II approach their landing site at Evreux, France, after completing the first successful transatlantic crossing by balloon.

HP programmable calculators have performed navigational computations on some extraordinary journeys before: the Apollo-Soyuz link-up in space and the America Cup yacht race, for example. But to our knowledge, this is the first time one has navigated the Atlantic in a balloon.

When three balloonists from Albuquerque, New Mexico, made aeronautical history by flying nonstop from the United States to France, they calculated their position every morning and evening with an HP-67 hand-held programmable calculator.

Balloonist Maxie Anderson took along an HP-67 together with a Navigation Pac of prerecorded programs designed for ocean-going vessels but also appropriate for a slow-moving balloon. While the HP-67 was originally intended as a backup for a most elaborate navigation system involving weather satellites, Goddard Space Flight Center, ham radio, and transatlantic commercial aircraft, response from the system took six or seven hours so that its precision was rather too retroactive for immediate use.

Shortly after crossing the coast of Newfoundland, as it happened, the aeronauts received word of an approaching storm. They needed to know their position, and they needed it fast. Unfortunately, Goddard's computers were tied up tracking a newly launched Venus probe, and couldn't help.

HP-67 to the rescue: balloonist Anderson measured the altitudes of Venus and Polaris, then spent a few minutes with his calculator and Navigation Pac, and was able to report his position to the ground crew by ham radio in time to turn the weather pattern to his advantage.

Thereafter, Anderson used his HP-67 each morning and evening to compute his position, which was confirmed six to seven hours later by data from Goddard. His fixes were within 20 to 30 miles of the satellite-derived positions—more than sufficiently accurate, considering that the horizon was 160 miles away. With a modern bubble sextant rather than his World War II surplus model, Anderson estimates his accuracy would have increased to within 10 miles.

HP programmables have successfully weathered a range of adverse environmental conditions—outer space, Mt. Everest, the Sahara, deep jungle—where reliability, accuracy, and quality were crucial. And while you may not be planning to navigate an 11-story-high bag of gas across the Atlantic, you can be certain that HP programmables will make your important calculations reliably and without "equal."

extend your possibilities.

The HP 250: A new, easy to use, small business computer with true data base management that adapts to your existing organization.

The HP 250 is the lowest-priced business computer available today with full data base management. HP 250 also offers forms and report-writing utilities; 128K bytes of system memory and 32K bytes of user memory, expandable to 64K; and built-in self test.

While it contains many big-system features, and includes powerful tools for developing applications, the HP 250 is exceptionally easy to program and operate. It is well suited for the end user, the OEM who tailors computer solutions for the small-business market, and larger companies that need easy-to-use systems for dedicated applications.

The careful attention to human engineering makes the HP 250 very approachable, especially for first-time computer users. The keyboard resembles that of an office electric typewriter with an adding machine's numeric pad as well. The video display screen, which swivels, tilts, and slides for viewer comfort, has eight "soft keys," with definitions labeled on the display screen. These keys can be programmed to guide the user through each task with step-by-step prompting. They're also very useful to a programmer writing applications software.

As a further convenience, the HP 250 can be placed in most office environments without special site preparation. Installation is a simple matter of plugging the computer into a standard electrical outlet.

The HP 250 provides complete data base management capability (IMAGE/250) which makes defining, creating, accessing, maintaining, and using complex data files a simple task. The information stored in the data base is available on command with QUERY/250, a simple, direct inquiry method that makes it possible to get stored information without writing an additional program. The FORMS/250 utility makes it easy for the user to put existing business forms on the HP 250. The user can then display the form on the video screen when needed for fill-in-the-blanks use. REPORT WRITER/250 provides formatting controls for computer-generated reports in complete or summary form.

Price of the standard system is $24,500*. The system includes two 1.2-megabyte flexible disc drives, a dot matrix printer, the data base manager, and all the application development tools described earlier. Storage for the system can be expanded through additional flexible discs or by adding fixed discs.

Even with all these technical advances, you don't have to be afraid of the HP 250. Turning the key initiates a self test that lets you know the system is operating properly and ready to do your task. And when it comes to maintenance, the CPU and memory boards are on a single, roll-out chasis to make it easy for HP-trained service personnel to keep the system in top form.

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Fusion Power with Particle Beams

In one approach to controlled fusion a pellet of fuel is imploded by an external energy source. Supplying the energy with intense beams of particles is being explored in the U.S. and the U.S.S.R.

by Gerold Yonas

Fusion, the kind of nuclear reaction that converts mass into energy inside the sun and other stars, is widely regarded as one of the most promising means of generating electric power for the next century and beyond. Research in this area has intensified dramatically since the oil embargo of 1973, and substantial progress has been made as a result of the expanded effort. Many workers now believe that the scientific feasibility of fusion power will be determined within the next decade. The period is crucial because several large "proof of principle" experiments should be completed in the 1980's.

Efforts to duplicate the fusion process on a controlled basis have centered principally on magnetic-confinement schemes, in which the hot gaseous fuel (a mixture of deuterium and tritium, two heavy isotopes of hydrogen) will be held within the reactor vessel by means of strong magnetic fields, and to a lesser extent on an inertial-confinement scheme that will rely on powerful laser beams to implode tiny pellets of deuterium and tritium. In the past few years my colleagues and I at the Sandia Laboratories in Albuquerque, N.M., and a larger group of investigators at the I. V. Kurchatov Institute of Atomic Energy in Moscow have undertaken a different approach to fusion by inertial confinement. Instead of laser beams we have employed intense beams of electrons (and more recently ions) generated by very-high-current, very-high-voltage electric pulses.

This approach to fuel-pellet implosion is potentially efficient, simple and economically competitive, but like all other approaches to fusion it requires solutions to a series of formidable technical problems. We can, however, report encouraging progress in our efforts. As a result this dark horse in the race to fusion power is attracting increased interest. It is likely that the winner of this worldwide competition will proceed beyond the proof of scientific feasibility to the first experimental power reactors and thence (perhaps early in the next century) to a demonstration power plant.

The idea of fusing the nuclei of hydrogen atoms to release energy for the generation of electricity is attractive for several reasons. One measure of the potential benefit from controlled fusion can be appreciated if one considers that a thimbleful of liquid heavy-hydrogen fuel would release as much energy (in the form of energetic neutrons) as 20 tons of coal. Even more important, the fuel is readily available. Deuterium is found in all natural bodies of water, and tritium can be synthesized by the reaction of fusion-generated neutrons with lithium in a "blanket" surrounding the reaction chamber. If the materials for the walls of the reaction chamber were carefully selected, the fusion reactor would have fewer radioactive by-products than a fission reactor. In addition there would be no possibility that the fuel core would melt down, a conjectured type of failure that has helped to make nuclear power plants the subject of controversy.

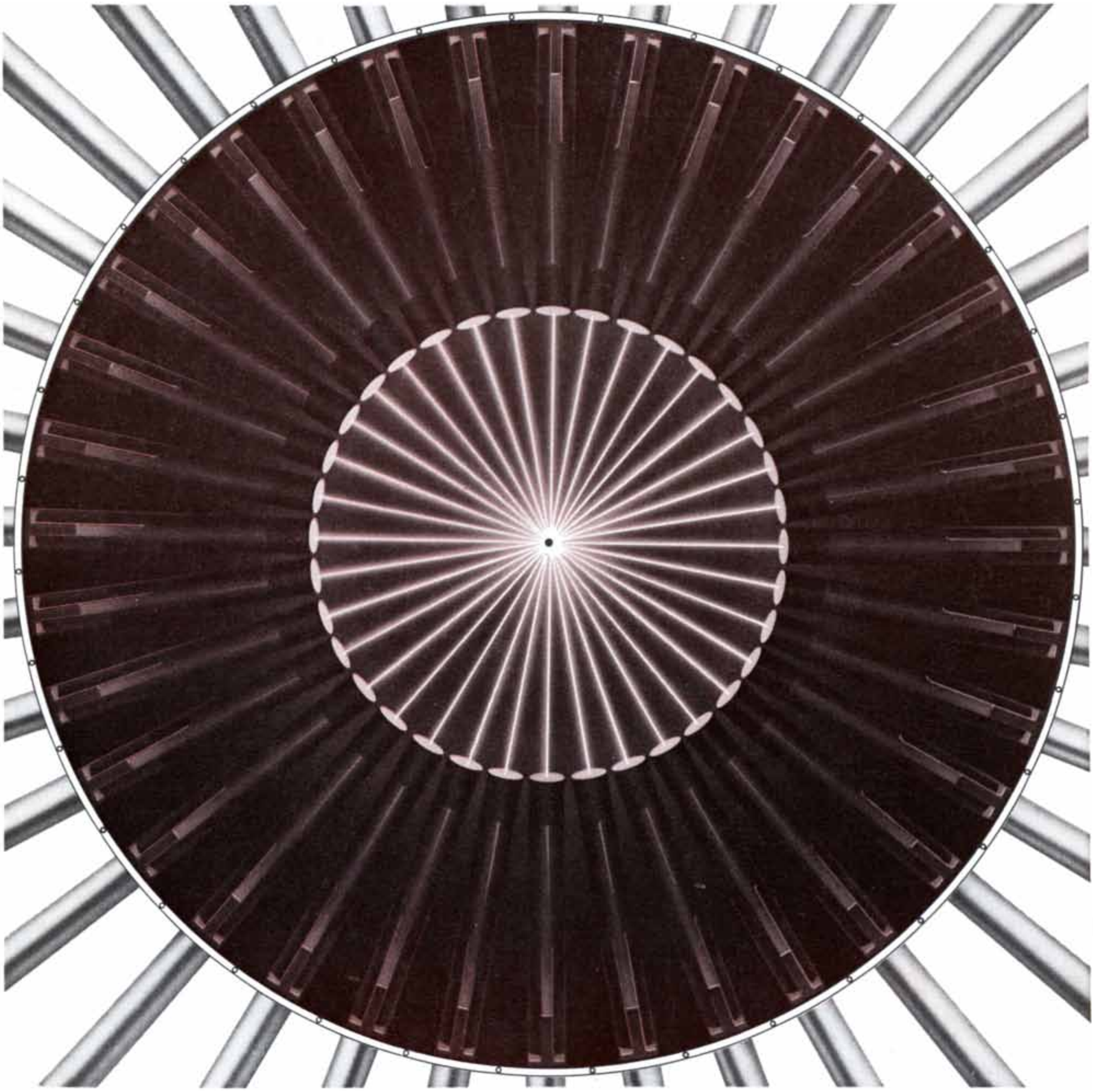
Nature has a way of coupling risk and reward, so that frequently those processes that have the greatest potential for benefiting mankind are also those that can be achieved only with the greatest difficulty. So it is with fusion. After nearly three decades of effort fusion ignition (that is, the efficient burnup of deuterium and tritium) has been achieved in only one way: the hydrogen bomb. Moreover, fusion has been achieved in this case only with a fission trigger (an atomic bomb) to generate the extremely high temperature and the degree of confinement necessary for the hydrogen nuclei to fuse.

The conditions necessary to gain any worthwhile net power from fusion reactions involving deuterium and tritium are formidable: a temperature of about 100 million degrees Celsius and a combination of fuel-confinement time (in seconds) and fuel density (in particles per cubic centimeter) whose product is greater than 10^{14}. The high temperature is needed to propel the nuclei to velocities sufficient to overcome their mutual electrical repulsion when they encounter each other. The required confinement time and particle density ensure that there are enough collisions for the reactions to proceed efficiently.

In the magnetic-confinement approach the fuel must be maintained at a fairly low density because of practical limits to the magnetic-field strengths that can be obtained. As a result confinement times of seconds or minutes must be achieved in order to get a substantial burnup of the fuel. In the inertial approach the fuel is heated as it is compressed to an extreme density (typically 1,000 times the normal density of the solid fuel). Under these conditions the fuel reacts so rapidly that the burning is actually a small explosion. Since the compressed fuel is restrained by its own inertia, it burns before it flies apart (in less than a billionth of a second).

As the cost of fusion research has escalated there has been considerable discussion not only of the potential benefits of fusion but also of its possible drawbacks. One of the primary concerns is that even if the physics problems are resolved and the needed technologies are adequately developed, the complexity, the materials requirements and the overall cost may still preclude the realization of a new energy source. Electric utilities have already expressed a desire for small, comparatively inexpensive demonstration experiments that can be brought on line rapidly and modified easily after operational experience has been obtained. The inertial-confinement approach to fusion may more nearly fit this requirement because it does not call for the large superconducting magnets and certain other costly complexities necessary for magnetic-confinement fusion; instead it seeks to achieve confinement by directing an intense energy source (either a laser beam or a particle beam) onto the outer surface of a spherical pellet, causing a rocketlike ablation of the surface and an implosion of the deuterium-tritium fuel mixture in the remainder of the pellet. The compression not only heats the fuel to the ignition temperature but also increases the amount of fuel that can be burned.

Magnetic-confinement fusion can be likened to a furnace, which requires ig-

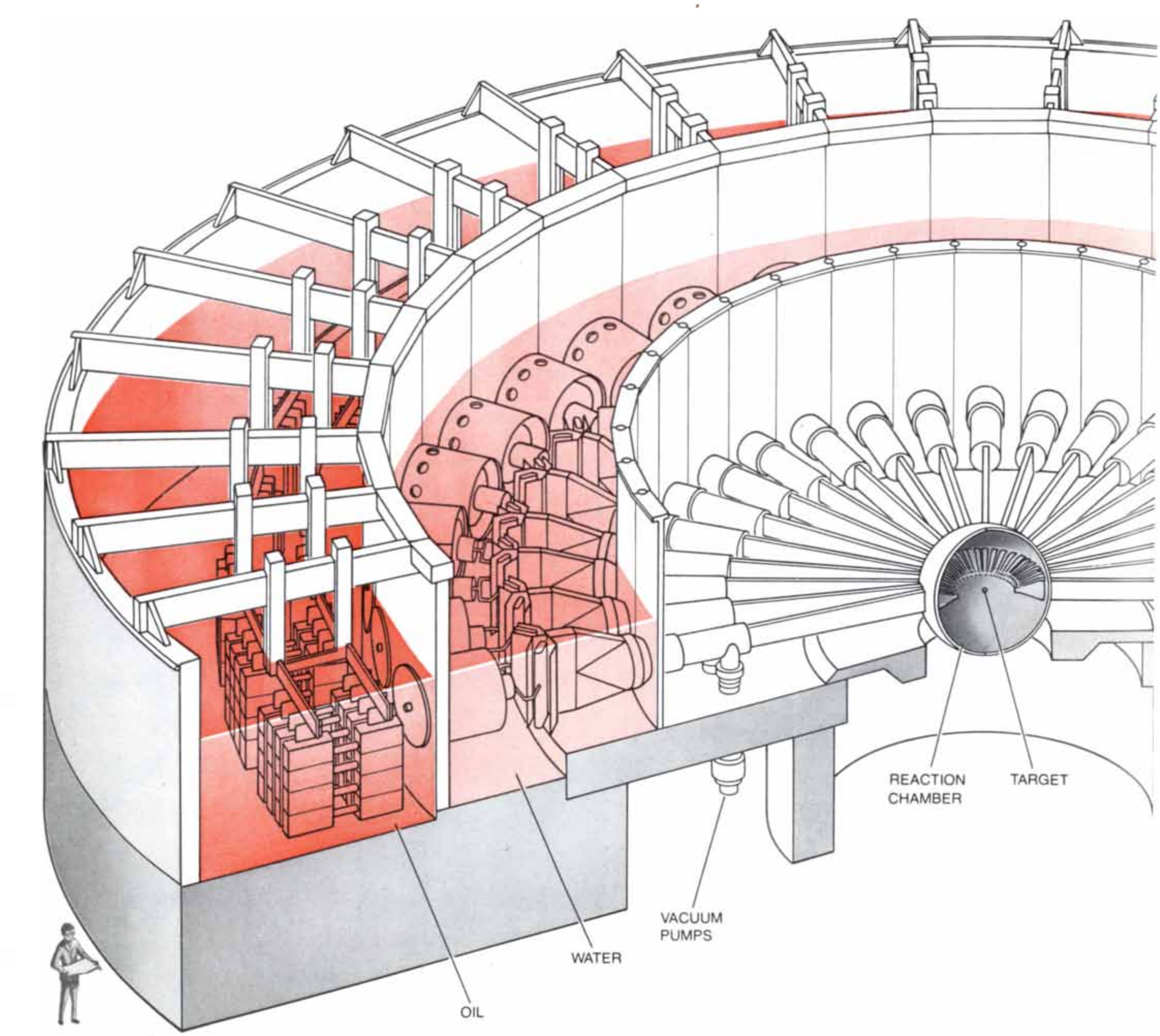


THIRTY-SIX ELECTRON BEAMS will be concentrated to implode a deuterium-tritium fuel pellet in the experimental electron-beam fusion accelerator now under construction at the Sandia Laboratories. This drawing shows a horizontal cross section of the reaction chamber, which will have a radius of 42 inches. The electron beams (*bright lines*) will be injected into the chamber from the front ends of 36 independent accelerator lines and will be propagated the last 18 inches to the target along dense, magnetized plasma channels formed in the air inside the chamber. When the device is completed and ready for testing late next year, it is expected to be capable of delivering electron pulses with a total power of 30 trillion watts to the target area; a planned upgrading could double the power level by 1983. Pellet-ignition experiments are scheduled for 1985. Accelerator could be adapted to produce pulsed ion beams for fusion research.

nition, refueling and the removal of impurities and which has a long burn time compared with the ignition time. Inertial-confinement fusion, on the other hand, requires an efficient, highly repetitive ignition system and a continuous supply of inexpensive fuel pellets, which are injected and ignited one at a time. In a hypothetical inertial-confinement reactor one ten-thousandth of a gram of fuel would be ignited every tenth of a second by a 100-trillion-watt pulse, yielding an average thermal output of a billion watts. (An ordinary automobile spark plug delivers 100 watts to its combustion chamber.) If a conventional thermal-to-electric conversion cycle is employed and the ignition system is 20 percent efficient, a power plant with an inertial-confinement fusion reactor at its core would deliver 350 million watts of electricity, enough to power a city of 175,000 residents. (It should be kept in mind that the 100-trillion-watt figure cited here is the peak power of a pulse whose average power is only about 20 million watts.)

Lasers are in many ways ideal for irradiating such pellets. These devices can generate extremely short pulses of radiation (lasting a billionth of a second or less), which can easily be focused onto the surface of a pellet from a distance with the aid of lenses or mirrors. Significant progress has been achieved in laser-fusion research in recent years, and large neodymium-glass and carbon dioxide lasers are under development by the U.S. Department of Energy with the aim of demonstrating fusion "break even" conditions before 1985.

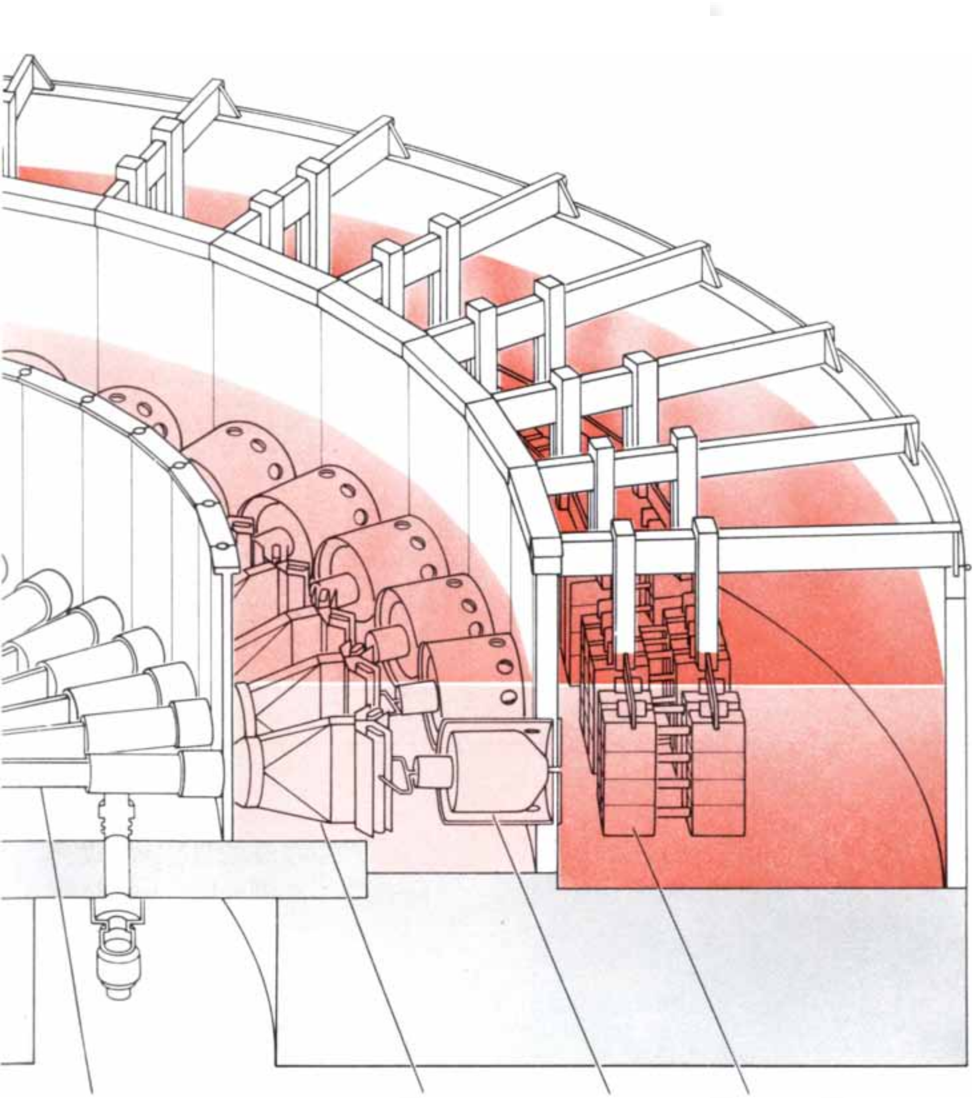
Lasers, however, have two serious disadvantages: they are inefficient and they tend to be expensive. For example, neodymium-glass lasers, the common-



CUTAWAY VIEW on these two pages shows the latest design of the Sandia electron-beam fusion accelerator. The reaction chamber is the spherical container at the center. The 36 magnetically insulated transmission lines leading into it are each about 22 feet long. The electron beams will consist of high-current pulses formed by electric discharges from a ring of 36 pairs of pulse-forming lines charged by capacitors (*barrel-shaped devices*). When the accelerator is in operation, the capacitors and pulse-forming lines will be immersed in a liquid di-

est high-power lasers, have an efficiency of only .2 percent, and their cost per unit of energy is currently about $500 per joule. The ultimate efficiency of carbon dioxide lasers is estimated to be between 5 and 10 percent, with that of present models ranging between 2 and 3 percent. There is much debate as to the ideal wavelength for a fusion laser, and a vigorous search is under way to develop efficient short-wavelength lasers. It was primarily the inefficiency of lasers that led to the present interest in beams of electrons or ions as pellet igniters.

The particle-beam approach to fusion has been made possible by the growth of pulsed-power technology, which began in the mid-1960's. This technology was supported by the Atomic Energy Commission and the Department of Defense to provide radiation sources to test the survivability of intercontinental ballistic missiles against bursts of radiation from anti-ballistic-missile warheads. To simulate these radiation effects powerful bursts of X rays were needed. The radiation that results when a multimillion-volt electron beam hits a thin foil of a metal such as tantalum proved to be adequate for the purpose. To meet the need for intense X rays and gamma rays, Thomas H. Martin and his group at Sandia, with the assistance of J. C. Martin of the British Atomic Weapons Research Establishment, developed in 1967 an electron-beam accelerator capable of discharging a maximum energy of 100,000 joules into an X-ray tube at an electric potential of 10 million volts. This trillion-watt accelerator, called Hermes, and a similar device developed by the Department of Defense embodied many of the components and concepts that are applied in today's pulsed-electron-beam accelerators.



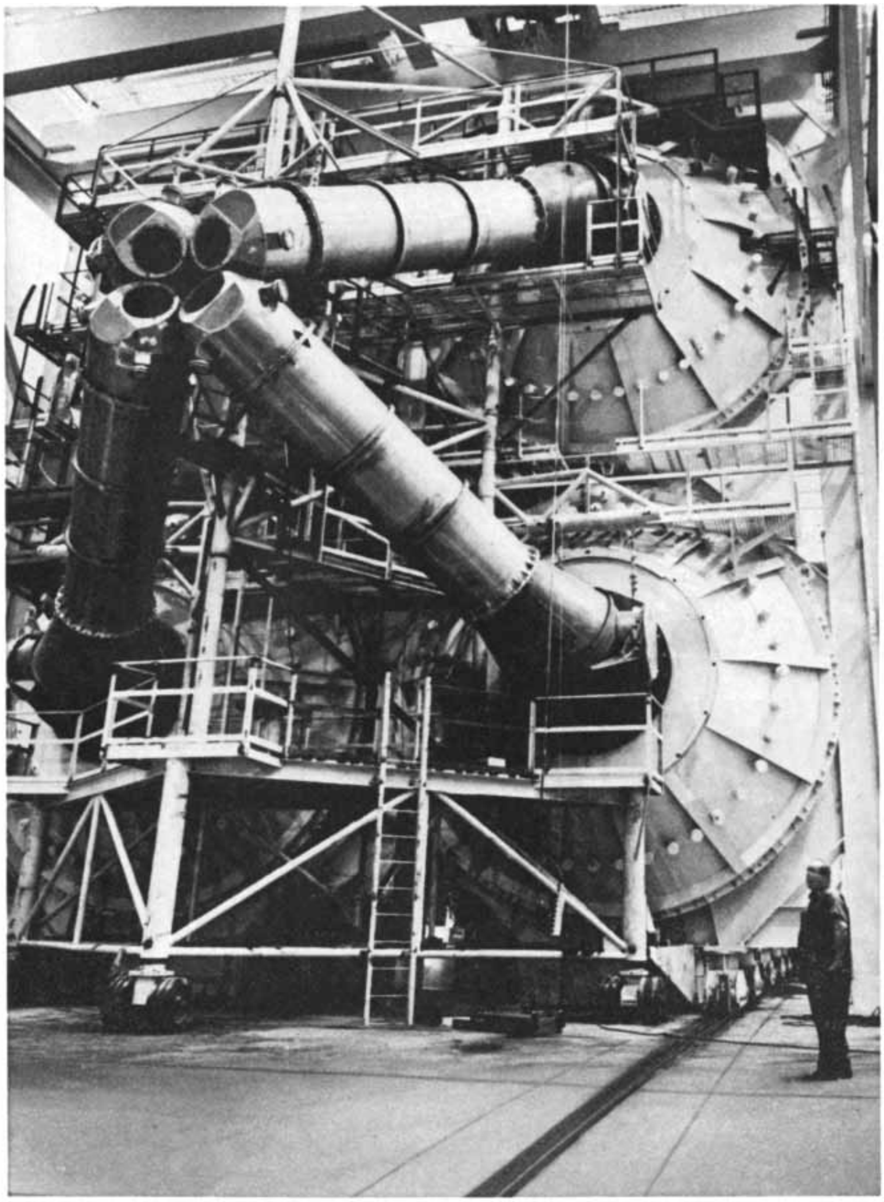
electric, in this case pure water (*light color*). The stored electricity will be supplied by an outer ring of high-voltage generators, which in turn will be insulated by transformer oil (*dark color*). The total energy delivered to the target area of the electron-beam accelerator will be on the order of a million joules. A somewhat larger experimental machine is planned in the U.S.S.R.

A high-energy electron-beam accelerator is a remarkably simple device whose components can be bought off the shelf or fabricated in an ordinary machine shop. It is basically a high-voltage source that stores energy in capacitors and then discharges the energy through switches into an insulated pulse-forming line and thence into a diode, or two-element, vacuum tube. Electrons are accelerated to the anode of the tube from a dense plasma (a superheated gas of charged particles), which forms on the metallic surface of the cathode as a result of self-resistive heating of microscopic surface protrusions. It is generally accepted that the required power for pellet ignition is 100 trillion watts. For an electron beam to deliver this power an operating current of between 10 million and 100 million amperes must be attained, calling for an accelerating potential of between one million and 10 million volts.

The most powerful electron accelerator in existence is the Aurora device, developed for the Department of Defense by Ian D. Smith and his colleagues at the Physics International Company and installed at the Army's Harry Diamond Laboratory near Washington, D.C., in 1972. This four-beam, 20-trillion-watt accelerator operates at an electric potential of more than 10 million volts and generates pulses lasting more than 100 billionths of a second. Although it does not have the right parameters for electron-beam-driven fusion experiments, its remarkable efficiency (50 percent) and comparatively low cost ($14.5 million) provide an impressive demonstration of pulsed-power technology.

The efficiency and cost criteria for particle-beam fusion igniters had not been formulated when the first proposal for their use in inertial-confinement fusion, put forward by A. John Gale of the High Voltage Engineering Corporation, was awarded a U.S. patent in 1963. In fact, Gale may have been the first to propose beam-driven inertial-confinement fusion, since lasers had only just been invented at the time he filed his patent disclosure in 1960. Shortly thereafter F. Winterberg of the Case Institute of Technology considered the hypersonic acceleration of small grains of matter for reaching fusion-ignition conditions on impact. By 1967, however, Winterberg realized that powerful electron or ion beams might be easier to produce. Between 1964 and 1967 Franklin C. Ford and his group at Physics International were also considering the electron-beam approach to pellet ignition in the course of their pioneering work on scaling pulsed-power technology up to the 100-billion-watt level. According to L. I. Rudakov, the leader of the Russian electron-beam program, E. A. Zavoiski at the Kurchatov Institute had also decided in 1968 to pursue the electron-beam approach, although the first Russian proposal did not appear until 1971. In spite of this flurry of interest, it took demonstrations of the scalability of the technology and tests of improved beam focusing (conducted at Sandia and other laboratories in the early 1970's) to catalyze an effort that led to support by the AEC in 1973.

Given the apparent efficiency, simplicity and low cost of high-energy electron-beam accelerators (the cost is even today estimated to be 2 percent of the cost of lasers of comparable energy), it is only reasonable to ask why the potential of electron-beam fusion was recognized so late. The answer is that this approach to fusion, like all other approaches, presents fundamental problems that are far from being solved. These problems include creating megampere pulses for tens of nanoseconds, producing tightly focused beams of charged particles, transporting the beams to the target and efficiently depositing the particles on the target. There have, however, been several major discoveries and innovations, at our laboratory and elsewhere, in the short time that the electron-beam approach has been pursued, and the technology itself has proved sufficiently flexible and inexpensive to accommodate to and benefit from these advances.



"AURORA," the most powerful electron accelerator in existence, was built for the Department of Defense by the Physics International Company to test the survivability of intercontinental ballistic missiles against simulated bursts of radiation from antimissile warheads. The four-beam, 20-trillion-watt device was photographed at the Army's Harry Diamond Laboratory near Washington, D.C. The accelerator operates at an electric potential of more than 10 million volts and generates electron pulses lasting 100 billionths of a second. Although Aurora is not suitable for fusion experiments, it demonstrates potential of pulsed-power technology.

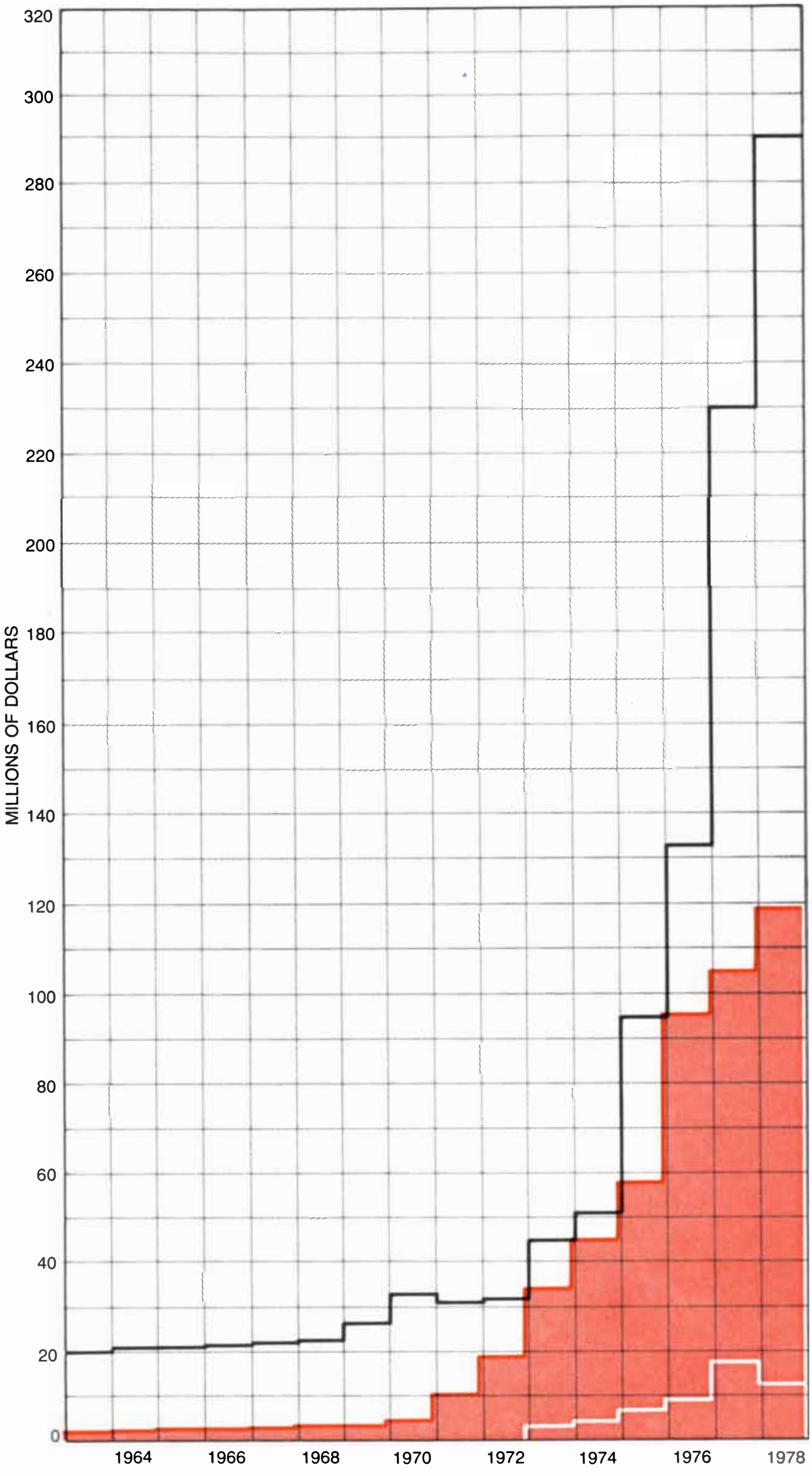
Perhaps the greatest advance has been made in the more precise understanding of the nature of the beams and how to focus them. Since electrons are charged particles, they repel each other, making focusing a much more difficult problem than it is with the photons from lasers. The problem can be overcome only by utilizing the "self-pinching" effect of the magnetic field generated by a high-current beam when the electric-repulsion force is neutralized. In a high-current diode the nearby metal surfaces reduce the electric force, and the magnetic field of the beam turns the electrons toward the axis of the diode. After drifting radially the electrons focus onto the anode at the axis where the magnetic field drops to zero. This phenomenon, which was first studied experimentally by Philip W. Spence and me at Physics International in 1967 and 1968, has since been more fully explained by James W. Poukey of Sandia, who developed a computer model that simulates the motion of trillions of electrons as they swarm within a diode. Similar explanations have also been provided by S. A. Goldstein of the Naval Research Laboratory, who has modeled diode behavior by means of simple analytical methods.

The self-focusing effect is now known to be strongly influenced by the flow of ions from the plasma that forms on the anode. This ion flow governs the dynamics of beam-pinching. At Sandia we were able to enhance beam-pinching in 1973 by preexploding a fine wire along the axis of the diode, thereby providing an additional source of plasma. Today it is possible to produce a dense electron beam with a diameter of two millimeters by means of passive plasma-forming techniques. The highest power densities achieved so far with such diodes have been produced by workers at the Kurchatov Institute: Rudakov has reported a power density of more than 10^{13} watts per square centimeter. High-power electron-beam diodes have operated efficiently at current levels of up to a million amperes, and it now appears that fewer than 100 diodes would have to be operated simultaneously to provide the total power necessary for the ignition of a pellet. The investigation of beam focusing has also resulted in findings indicating that a high-current electron beam behaves more like a gas than like a bundle of particles following a parallel path to the pellet. The random motion of the electrons within the beam allows the entire surface of a spherical pellet to be evenly bathed when the pellet is irradiated with only a single beam. Actually this single-beam method of irradiation was employed in our first successful neutron-producing experiments.

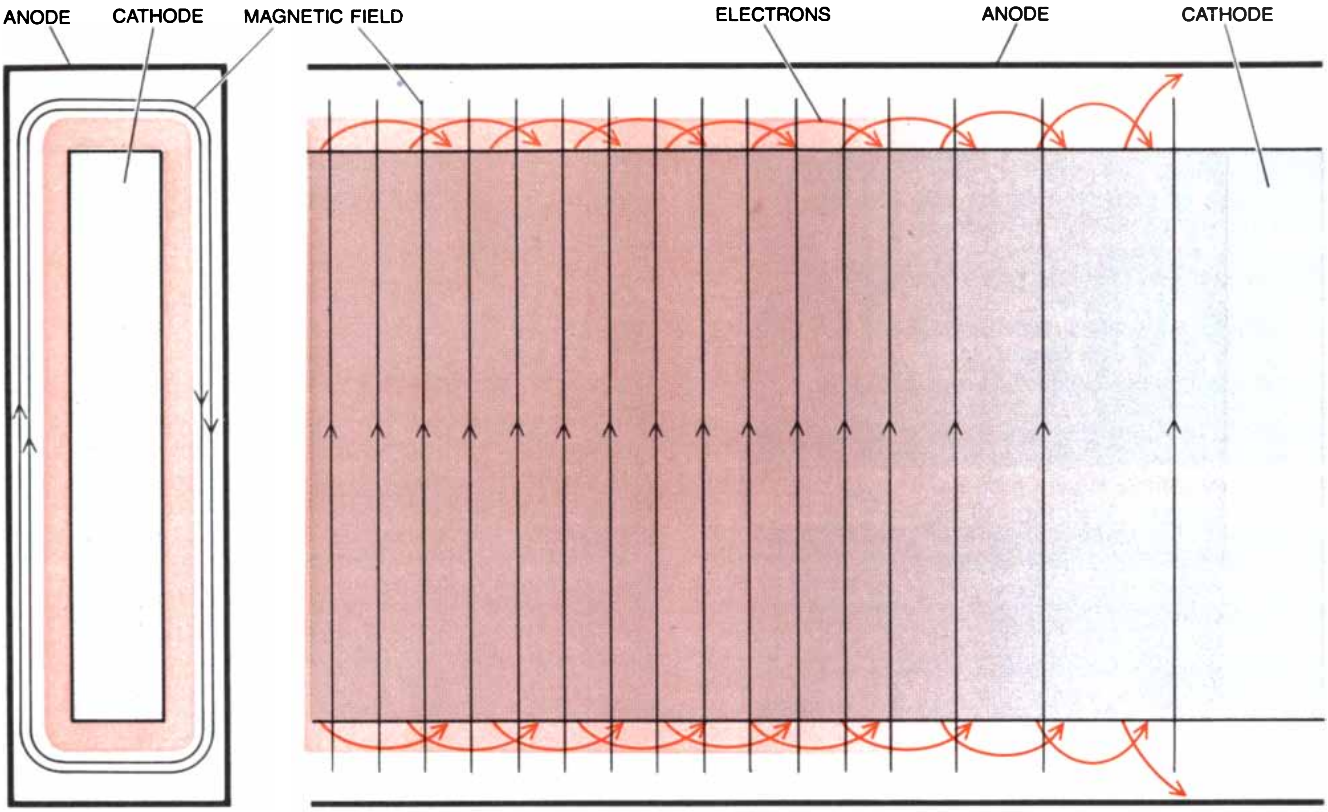
In addition to improvements in beam focusing, the technological questions of pulse formation have largely been answered in the past five years through the development of high-power switches and an improved understanding of electric breakdown. So far we have been able to switch pulses of up to eight trillion watts with a duration of 24 nanoseconds. Contemporary target designs for particle beams make it seem unlikely that shorter pulses will be needed. In 1974 fast high-voltage switching in an oil dielectric was achieved by Kenneth R. Prestwich of our laboratory with triggered rail-gap switches based on a concept developed by J. C. Martin; total power levels of up to a trillion watts have been switched with this technique.

When it became necessary to increase the density of the electric energy in the circuit, the oil dielectric was replaced with water and a different switching technique was instituted. (Pure water is an excellent insulator for periods of one or two microseconds; it has a dielectric constant 81 times that of a vacuum, compared with oil, which has a dielectric constant only three times that of a vacuum.) In a water dielectric a new switch was required because with the shorter, higher-energy-density transmission lines there was less room for a triggered switch. The answer to the problem was a self-triggered switch to which an additional pulse-forming line provided a rise in voltage short enough to create multiple breakdowns and numerous current-carrying channels in the water. This type of switch has since been used in a system producing a five-million-ampere pulse that rises to its peak in less than 20 billionths of a second.

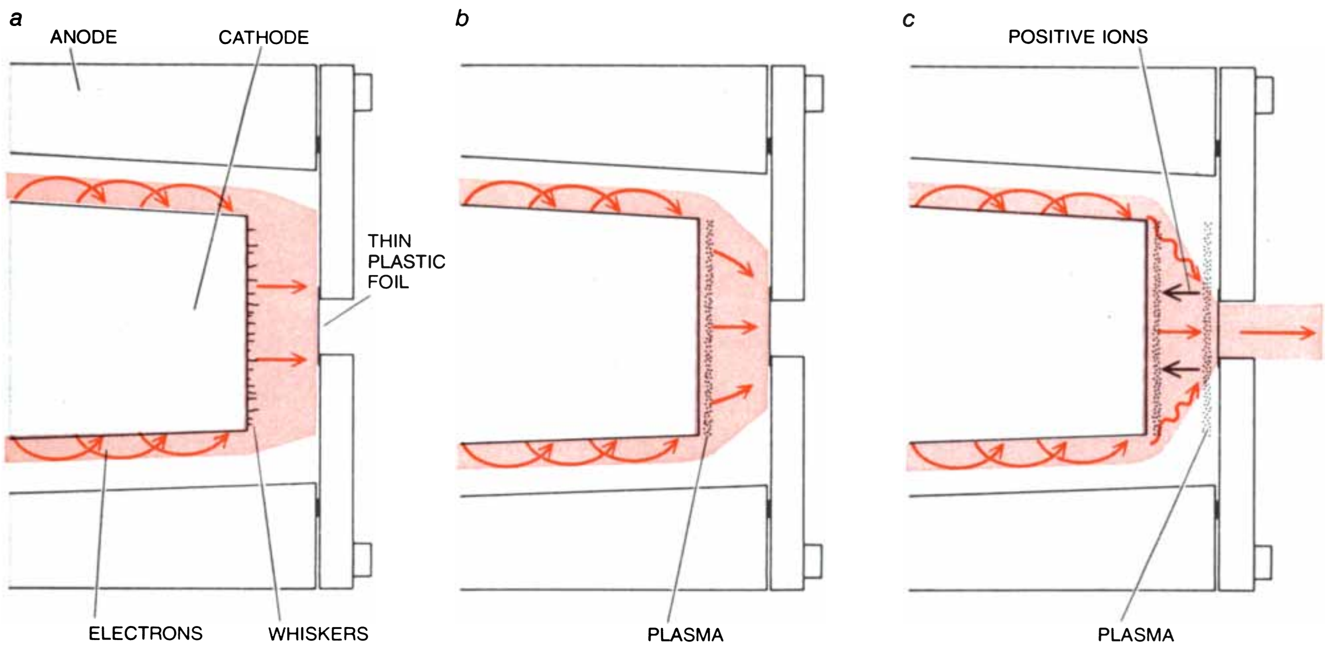
Although the technology of transferring high-energy pulses through liquid dielectrics has evolved rapidly, the spatial concentration of the pulse has been a more difficult problem to solve because of electric breakdown in the accelerator itself. The weakest point in the power-compression chain has been the solid insulating interface between the water-insulated pulse-forming line and the diode chamber containing the fuel



ANNUAL FUNDING LEVELS for different kinds of fusion-power research in the U.S. are compared in this bar chart. The budget for research on magnetic-confinement fusion (*black line*) remained fairly constant from 1958 until 1974, when the rapid rise began to the current level of some $300 million per year. The budget for the inertial-confinement fusion program (*colored line*) started to increase in 1971 and by 1973 reached a level comparable to that of the magnetic-confinement program. At present research on inertial-confinement fusion (which includes both the laser technique and the particle-beam technique) accounts for about 30 percent of the total U.S. budget for fusion research. Portion of the inertial-confinement budget devoted to particle-beam research (*white line*) is less than 3 percent of national fusion effort.



MAGNETICALLY INSULATED TRANSMISSION LINE will carry the electron pulses to the reaction chamber in the new Sandia electron-beam fusion accelerator. In this pair of diagrams the megampere electron flow is shown in color; the intensity of the color corresponds to the concentration of the electrons in different parts of the pulse. As the pulse travels down the central cathode of the transmission line, it sets up a transverse magnetic field (*black arrows*) that inhibits the electrical breakdown of the vacuum gap separating the cathode from the surrounding anode. Ahead of the pulse the electrons (*colored arrows*) tend to escape from the cathode to the anode, losing energy. Within the body of the pulse, however, the strong self-generated magnetic field forces electron flow to keep to surface of cathode.



SELF-FOCUSING EFFECT will enable the electrons flowing along the cathode of a magnetically insulated transmission line to focus onto the anode at the axis where the magnetic field drops to zero. The effect is strongly influenced by the formation of a plasma layer (*black stippling*) on the face of both the cathode and the anode. Initially the electrons are emitted from microscopic surface protrusions ("whiskers") on the cathode and are accelerated to the anode in a relatively unfocused beam (*a*). The explosion of the heated whiskers forms a plasma (a hot gas of charged particles) on the surface of the cathode, intensifying the flow of electrons across the gap between the cathode and the anode. The electron flow heats the surface of the anode, forming another plasma layer there (*b*). The reverse flow of positively charged ions (*black arrows*) from the anode plasma to the cathode plasma helps to neutralize the self-repulsive force of the electrons, thereby sharpening the focus of the electron beam as it passes into the reaction chamber through a small hole in the face of the anode (*c*).

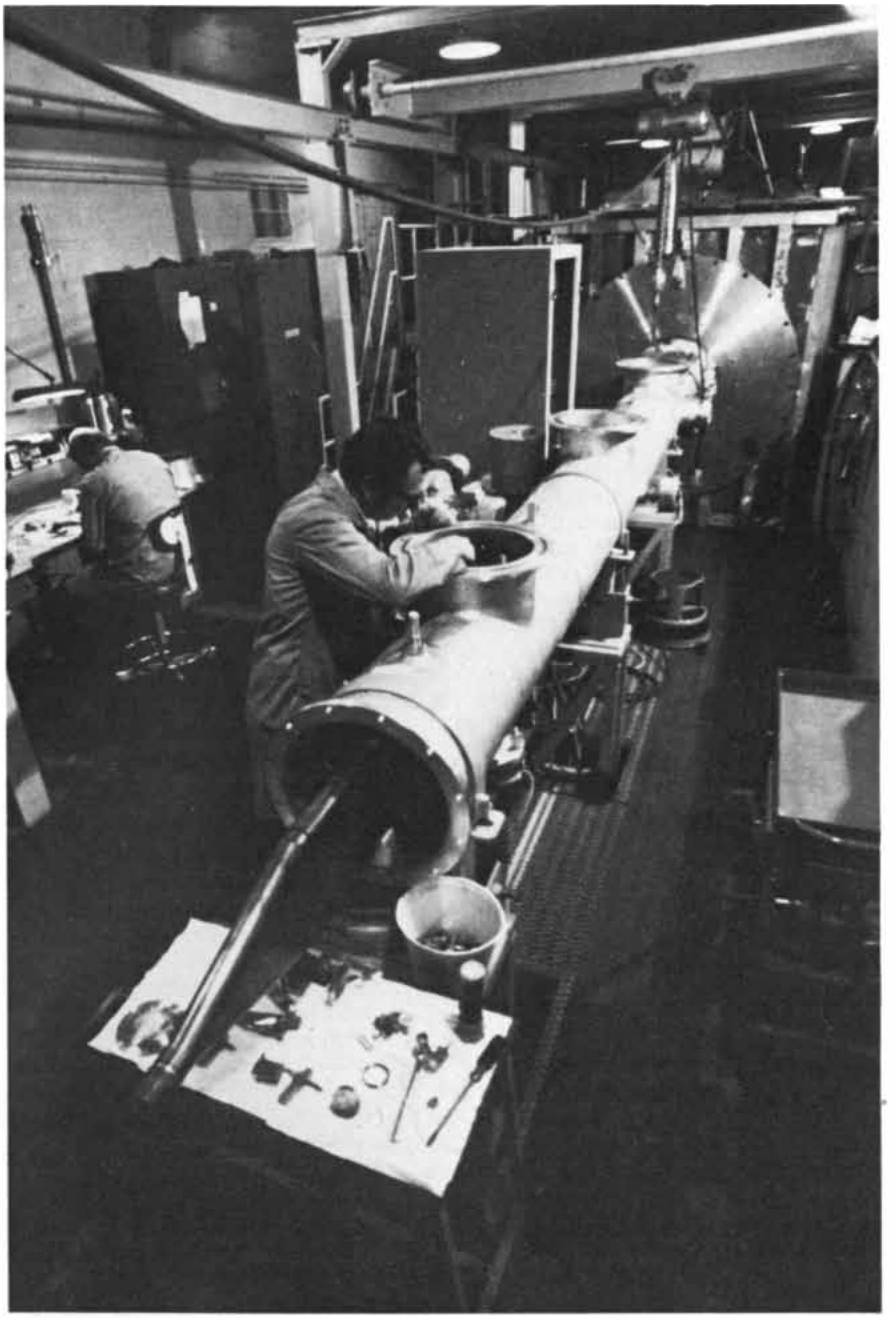
pellet. The interface, which is made of plastic, can typically withstand a stress of only 100,000 volts per centimeter and therefore it can carry only 25 million watts per square centimeter at its surface. This constraint means that the 100 trillion watts needed for a fusion reactor would call for an interface with an area of four million square centimeters. If the rise time of the pulse is lengthened, the power density can be further increased to about 100 million watts per square centimeter; nevertheless, delivering the needed power through a single module would present many practical difficulties and would essentially require that very-high-current beams be compressed in radius over a distance of many meters.

A solution to the problem of power concentration has now been demonstrated as a result of work at Physics International, the Kurchatov Institute and Sandia. The approach calls for the employment of magnetically insulated transmission lines, a concept that relies on enhanced electrical insulation in a vacuum instead of in a liquid or solid dielectric. Normally when a low-power pulse is transferred along an evacuated transmission line, electrons are emitted from the negatively charged electrode when the electric field exceeds 200,000 volts per centimeter. Under these conditions much of the energy is lost over a short distance instead of being transmitted along the line as an electromagnetic wave. Because of this limitation the maximum power density that could be transmitted by a short pulse in a vacuum would be 100 million watts per square centimeter; hence a coaxial line of useful dimensions, say 30 centimeters in diameter, would transport little more than 100 billion watts.

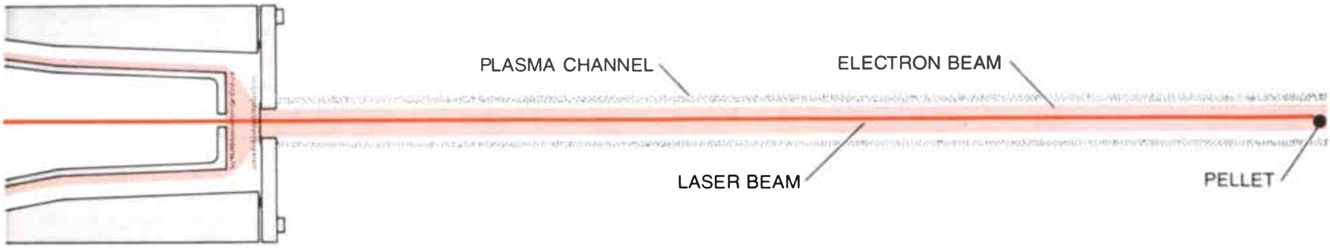
It has been found, however, that at very high power levels the transverse magnetic field of the propagating wave deflects the electron orbits so that their radius of curvature is smaller than the spacing between the electrodes. Under this high-power condition the emitted electrons are actually returned to the high-voltage electrode without losing energy, and power levels exceeding a trillion watts can be transmitted through the 30-centimeter line. That effect, which is observed to a limited extent in an ordinary tube of the magnetron type, was first observed in the Hermes accelerator in 1967. The feasibility of the approach was demonstrated for the first time in power transmission over a substantial distance in the Aurora accelerator in 1972. The four coaxial lines in Aurora efficiently deliver 20 trillion watts of power over six meters at a stress of 500,000 volts per centimeter.

Analysis and computer simulation of this important discovery have been under way for some years, but it has been only in the past two years that the concept has been rigorously tested and has come to be well understood. The principle was applied and extended at Physics International, which has demonstrated power transport over seven meters at an efficiency of 77 percent. A new two-dimensional computer simulation at Sandia has now demonstrated how the effect is achieved. The computer results show that at the head of the electromagnetic pulse the electrons reach the outer, or grounded, electrode but that within a short distance into the pulse they are turned back by the rapidly rising magnetic field, and the power is hence transported efficiently down the line.

Our group at Sandia has recently begun a thorough test of the concept of the magnetically insulated trans-



SINGLE PROTOTYPE MODULE of the 36-module electron-beam fusion accelerator is currently being tested at Sandia. The magnetically insulated test line, seen partially disassembled in this photograph, is fed by an electron pulse from two compact water-insulated pulse-forming lines (*out of sight behind the large circular plate at rear*). The test line itself consists of three parallel plates (one central cathode flanked by two anodes) enclosed in a cylindrical vacuum chamber. In a recent demonstration electrons were transmitted along the line at a power level of 800 million watts with an efficiency of almost 100 percent. Goal of these experiments is to produce a focused electron beam with a power density of 10 trillion watts per square centimeter.



PROPAGATION of a beam of electrons in the air-filled reaction chamber of a fusion accelerator will be accomplished by providing a dense magnetized plasma channel within which the focused electron beam can be guided from the end of the insulated vacuum line to the fuel pellet at the center of the chamber. In the initial experiments with the new Sandia 36-beam device an array of fine tungsten wires running from the diodes to the target will be used to guide the discharges within which the beams are to be propagated. In future experiments pulsed laser beams will serve the same purpose by creating weakly ionized narrow paths to the target. Latter design is illustrated here.

mission line, working with a variation of the basic idea to enhance further the concentration of power near the target. These tests are being conducted on a single prototype module of the 36-module, one-million-joule electron-beam fusion accelerator, which is now under construction and scheduled for pellet experiments after 1980. The test line, fed by a pulse from two compact water-insulated pulse-forming lines, is seven meters long and consists of three parallel plates enclosed in a cylindrical vacuum chamber. The three-plate configuration makes it possible to achieve a greater power concentration than can be achieved with a coaxial cable. In experiments carried out by Pace J. Van Devender a power-transport efficiency of almost 100 percent has been demonstrated at power levels of 800 billion watts. A power density of more than 100 billion watts per square centimeter has already been achieved over a small section of the transmission line, and tapering the line should increase the power density further. Our goal is to produce a focused electron beam of 10 trillion watts per square centimeter at the end of the transmission line; the degree of focusing already achieved makes us optimistic that this goal can be attained.

Transporting the focused beam from the end of the transmission line into a diode chamber containing the fuel pellet is the next and final link in the energy-transmission chain. Until the concept of the magnetically insulated transmission line was fully developed, most of our research at Sandia involved accelerators in which the electromagnetic wave emerged from the liquid dielectric, passed through the solid insulating wall of the vacuum diode and split into two beams that drifted radially from two cathodes to a pellet at the axis of the diode. This configuration evolved not only because of the focusing forces, which naturally cause the beam to pinch toward the axis, but also because of our wish to irradiate the pellet uniformly with two beams and to separate the diode insulator from the blast of the exploding pellet. Because of limitations on dielectric breakdown of the surface of the solid insulator this concept has given way to the newer one of the magnetically insulated transmission line, but there still remains the substantial problem of transporting the focused beam from the end of the insulated vacuum line to the center of the reaction chamber where it must strike the injected pellet. Recently, however, there has been progress in providing a sufficient "standoff" separation between the exploding pellet and the beam injector for the focused beam to be propagated.

In the propagation of an intense electron beam it has been found that a dense plasma containing a strong magnetic field acts as a beam conduit, with little beam energy lost over distances of a few meters. The possible instability of the beam, however, has caused concern because it could lead on a microscopic scale to the dissipation of energy or on a macroscopic scale to the "snaking" of the beam or its breakup into tiny, unstable filaments. These effects have been addressed by many investigators, and the conclusion is that high-current beams can be propagated if the plasma is dense enough and has a high enough electrical conductivity.

Beam transport therefore seems to hinge on finding a convenient means of creating a dense magnetized plasma channel without using massive field coils, which would themselves be damaged by a successful pellet explosion. Two years ago Paul A. Miller and I noted that a guided discharge in air satisfied most of the requirements for the plasma channel. Such a guided discharge, which can be initiated by a comparatively small bank of capacitors, serves not only to heat the air to a plasma along a narrow path but also to generate the magnetic field that guides the particle beam to the target. A close look at such a plasma channel with the aid of a holographic technique shows a uniform and stable low-density path surrounded by a denser and cooler cylindrical shell of gas that was pushed out of the channel. At Sandia and at the Naval Research Laboratory high-current electron beams ranging up to hundreds of thousands of amperes have been propagated efficiently by means of this technique. So far a fine tungsten wire running from the capacitor to a target has been used to initiate the discharges; in the future it is expected that a weakly preionized path created by a laser will serve the same purpose for the repetitive pulses of a fusion reactor. Although such reactor considerations are now beginning to receive attention, our immediate problem is still to demonstrate the feasibility of igniting the target pellet.

Of all the problems the electron-beam approach to fusion faces, energy deposition is one of the most critical. The efficient deposition of high-voltage electrons requires that the particles be stopped in a thin outer layer of the pellet. In order to reduce the amount of mass needed to stop the particles and so reduce the amount of energy needed to heat the mass it is important to utilize the effects of the beam's self-generated field or to utilize external fields for shortening the range of the particles in the pellet. For example, a million-volt electron normally deposits only 10 percent of its energy in a gold foil 10 micrometers thick. If, however, the self-generated field of a tightly focused million-ampere beam penetrates the material, electron penetration is effectively reduced and absorption efficiency may be increased to 50 percent.

In a sense this effect is attributable to the "stagnation" of the beam, which allows each electron to have more opportunities to interact with the atoms in the foil through ordinary collisions. The most dramatic demonstration of the effect was announced in 1977 by members of Rudakov's group, who reported heating a 10-micrometer gold foil to almost a million degrees C. with a 10,000-joule electron beam focused to a diameter of two millimeters. Their feat, which represents a deposition enhancement of approximately tenfold, has been partially reproduced (at somewhat lower power densities) in our laboratory.

Assuming that an efficient deposition

of energy can be obtained, the next question is one of target design. We have learned from our design studies that targets for particle-beam fusion are of necessity larger (perhaps as big as half an inch in diameter) and more massive than laser targets because of the longer duration of our pulses and the focusing limitations of energetic charged particles. Because of the greater mass of particle-beam targets they need much higher input energies, but that is not inappropriate for pulsed power, which tends to be rich in energy and comparatively poor in delivered power. In other words, we can deliver rather large energies in long pulses, and we need to have targets that reach the required fuel temperatures with slow implosion velocities.

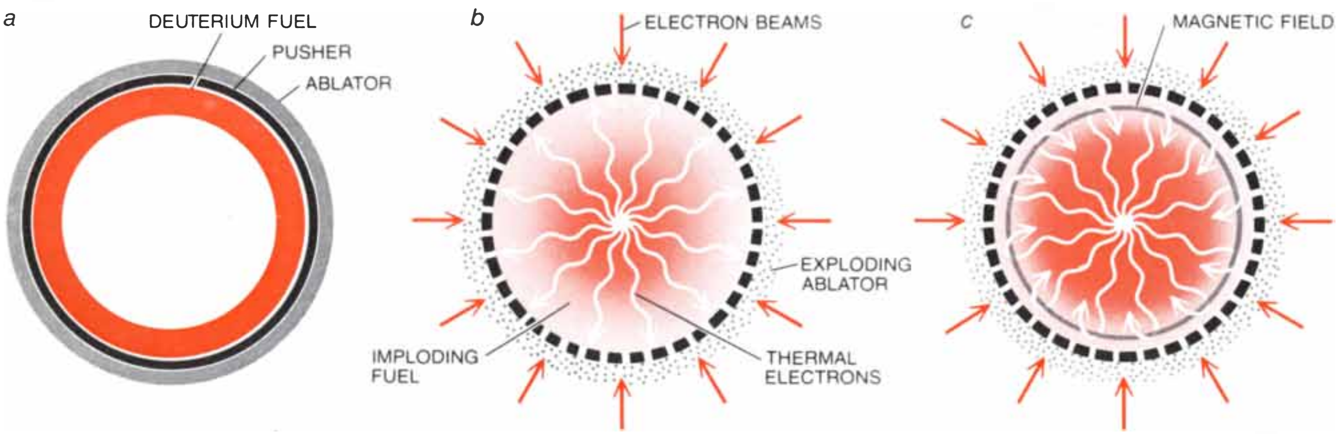
A target concept that may meet these needs was first developed in the Russian laser program under N. G. Basov at the P. N. Lebedev Physics Institute. In 1975 Basov and his group proposed using rather large, hollow targets consisting of several contiguous shells, which could be imploded over several tens of nanoseconds. The input energy would be accumulated during the relatively long implosion time and concentrated in the fuel only at the last stage of fuel collapse. The inner layers of the hollow shell would consist of a thermally insulating material, such as gold, surrounding a thin layer of fuel, which would implode first and become a superheated spot at the center of the target, thereby centrally igniting the rest of the imploded fuel. A related approach, based on multiple, noncontiguous shells, was proposed at the Lawrence Livermore Laboratory of the University of California last year. This design made use of thick shells, thus avoiding the "high aspect ratio" of the shells used in the Russian approach. The thicker shells reduce the possibility of hydrodynamic instabilities, which could destroy the symmetry of the implosion.

The stability of implosion has been the subject of considerable debate because quantitative implosion experiments have not been possible with the small beam energies available to date. This question should be answered in the near future. Targets that ignite at the center, which will be emphasized in future work, probably hold the key to reaching ignition and efficient burn conditions with low power levels.

Working with enhanced electron deposition and a multiple-shell design, members of Rudakov's group were able in 1976 to get the first measurable fusion-generated neutrons from a pellet irradiated with electron beams. They operated at a modest power level (less than 100 billion watts) but employed a five-micron-thick gold foil overlying a 10-micron-thick polyethylene foil to compress and heat the fuel, which was contained within a conical lead plug. At Sandia we got a similar number of target neutrons (about a million) in 1977 by adopting a concept from magnetically confined fusion: the application of a magnetic field to thermally insulate preheated fuel in the pellet from a surrounding high-density shell. In this way a slower implosion velocity can be employed, allowing longer pulses and less stringent beam-focusing requirements. The fuel was preheated and the trapped magnetic field was produced just before implosion with a high-current discharge through a filament within the pellet. In this way the million neutrons were obtained from a deuterium fuel with a comparatively slow implosion velocity of four centimeters per microsecond. (For the purposes of comparison the first successful laser pellet implosions occurred at 20 centimeters per microsecond.)

The complexity encountered in the physics of energy deposition and in the design of targets for electron beams has recently heightened interest in the use of ion beams for inertial-confinement fusion. Beams of light ions can be generated with existing electron-beam accelerators, although at a slightly reduced power, by suppressing the normal electron current. The range at which ions are deposited in a pellet is shorter than that at which electrons of the same kinetic energy are deposited; this should ease the requirements for both pellet design and beam generation. For example, our calculations show that the irradiation of a magnetically insulated target with a 10-trillion-watt beam of ions would yield a net energy gain; calculations that consider a magnetically assisted central-ignition pellet yield energy gains of more than 10 with absorbed ion-beam power levels of less than 50 trillion watts. This high gain requirement should be within the capability of an upgraded version of the Sandia electron-beam fusion accelerator, which is proposed for completion by 1983. High-voltage ions are very difficult to focus, however, and work has only just begun on the development of various schemes for concentrating the ion beams.

The initial approach to ion-beam production, proposed by Winterberg, was



IMPLOSION of a heavy-hydrogen fuel pellet depends critically on the design characteristics of the pellet. The hollow multiple-shell design shown (*a*) consists of an inner shell of deuterium fuel (*color*), an outer shell of explosive "ablator" material (*gray*) and an intermediate "pusher" shell (*black*) to help compress and heat the fuel symmetrically. The incoming electron beams explode the ablator shell (*b*), driving the inner layers toward the center and igniting fusion reactions between deuterium nuclei in the fuel. In order to help insulate the imploding fuel from the surrounding high-density pusher shell workers at Sandia have produced a trapped magnetic field within the pellet by discharging a high-current electric pulse through a filament embedded in the pellet; energy that would otherwise be lost to the pusher layer through the conduction of heat by thermal, or slow, electrons (*wavy white arrows*) is thereby confined to the implosion region, raising the final temperature of the fuel (*c*). Using this approach, James S. Chang and his colleagues have managed to obtain as many as a million neutrons from a deuterium fuel pellet with a comparatively slow implosion velocity of four centimeters per microsecond.

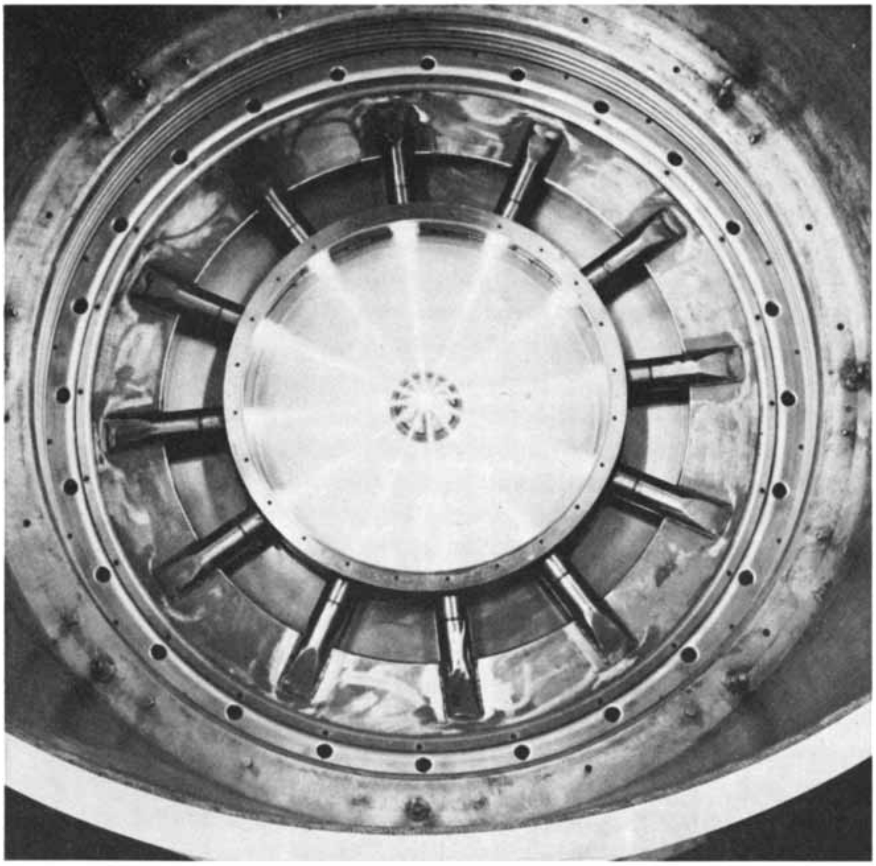
to suppress the electron flow in a diode by employing a magnetic field to prevent electrons from reaching the anode. The suppression is necessary because in a parallel flow of both electrons and ions through a diode most of the energy is carried by the lighter particles: the electrons. If, for example, the ions were protons, the proton current would be roughly 2 percent of the current of the electron beam. Applying a strong magnetic field parallel to the surfaces of the anode and the cathode with pulsed coils diverts the electrons, so that they form a rotating cloud, whereas the field only weakly perturbs the ions, so that they can pass through holes or slots in the cathode. If a supply of electrons is then made available outside the diode, the ions should be neutralized and propagated in straight paths. If the diode is shaped properly to direct the ions to a common point, an intense focus should be formed. The concept was first tested by R. N. Sudan's group at Cornell University. At Sandia, David J. Johnson and Glenn W. Kuswa have recently produced such an ion beam with a power of 500 billion watts. This power is approaching that of electron beams, but it remains to be seen whether a large enough force neutralization and a small enough beam divergence can be gained to focus the ion beam geometrically.

Another approach to the generation of ion beams and the suppression of electrons is being examined by Goldstein and Gerald Cooperstein at the Naval Research Laboratory. They are relying on the self-generated magnetic field of a high-current diode to limit the flow of electron current to the anode. Since they apply no additional magnetic field outside the diode, force neutralization may be achieved more readily. In this way they have produced an ion beam with a power of 300 billion watts and an efficiency of 50 percent; moreover, they have employed a simple geometric focusing scheme to achieve a current density of 70,000 amperes per square centimeter.

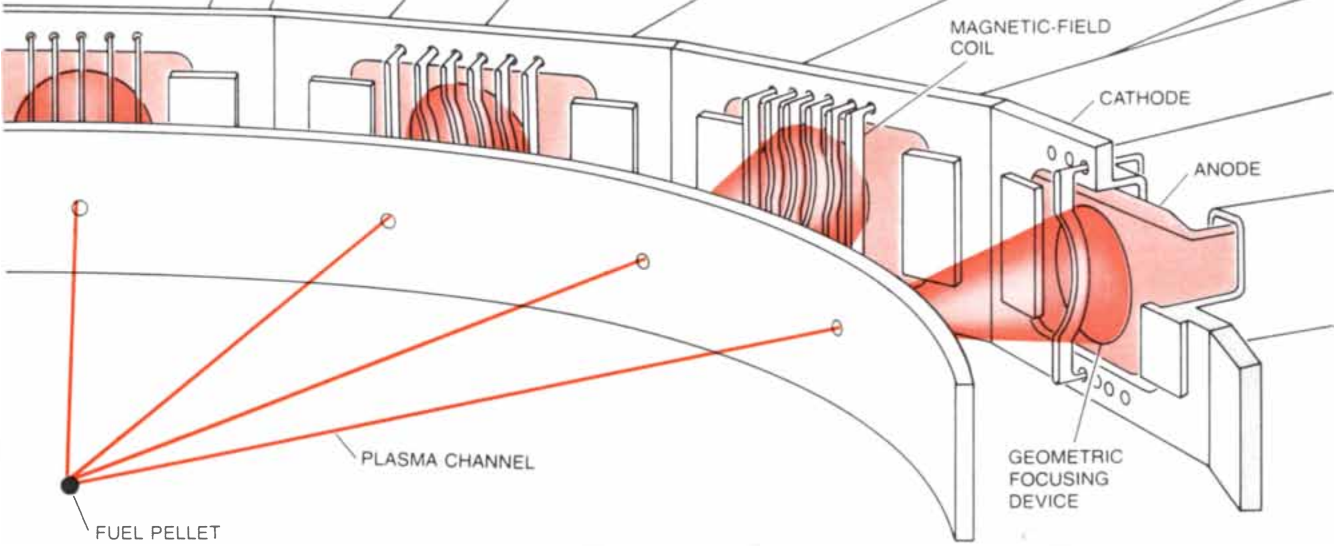
We are preparing to operate the Sandia electron-beam fusion accelerator in both the electron and the ion modes so that both options can be fully evaluated. In one diode design multiple ion beams would be generated at the end of the magnetically insulated transmission lines and geometrically focused over a distance of about a meter. These focused beams would then be transported to the target in plasma-discharge channels. The accelerator will also be used to evaluate a "beam bunching" concept that is applied routinely in conventional particle accelerators: increasing the power of the ion beam by compressing the ion pulses in both space and time. Such space-time compression is possible because ions in the energy range of a few megavolts are comparatively slow-moving, and if the accelerating voltage is increased over the period of a pulse, the faster ions at the end of the pulse can be made to overtake the slower ions injected earlier, providing a shortened pulse and a higher power at the target. In this way a power gain of at least 5 can be achieved.

A more recent approach to particle-beam fusion is the acceleration of heavy ions. Some physicists who have participated in the building of high-energy accelerators for research on elementary particles have proposed that conventional accelerator technology might prove to be adaptable for fusion reactors. They have noted that by employing heavy ions the necessary power could be achieved at much higher voltages and therefore lower currents. One of the most important advantages of operating at a high voltage would be that power could be delivered to the beam in successive, physically separated stages, thereby greatly easing the task of power concentration. The technology and economics of such an approach are now being investigated.

The U.S. program to develop the 100-trillion-watt electron accelerator needed for inertially confined fusion experiments began in earnest in 1974 with the development by Prestwich at Sandia of a trillion-watt accelerator named Proto I, which was placed in operation in 1975 and is now operating primarily in the ion-beam mode. Following that step Thomas Martin and his group began research that culminated last year with the successful operation of an eight-trillion-watt accelerator: Proto II. Many of the energy-storage, switching and pulse-forming elements for the next-generation accelerator have been successfully tested in Proto II. Experiments involving multiple ion beams and electron beams are under way on Proto II to provide the beam-propaga-



LUMINOUS PLASMA CHANNELS used to transport 12 high-energy electron beams are seen arrayed around a central target (here an aluminum post) in this demonstration photograph of the interior of the eight-trillion-watt Proto II electron-beam accelerator at Sandia. The channels were created in the ambient air by the discharge of a capacitor bank capable of generating currents of about 60,000 amperes per channel for a few microseconds. (For the purpose of the photograph the system was operated at about 12 percent of full power.) Normally this view of the plasma channels is obscured by the top of a cylindrical vacuum chamber approximately a meter in diameter. The 12 brass-tipped cathodes just outside the wall of the vacuum chamber inject 12 independently accelerated electron beams into the preformed plasma channels. The beams then drift to the central target area, where they are combined. This experimental 12-beam apparatus is being used to study the transport properties of both electron and ion beams.



POSSIBLE ADAPTATION of the new Sandia electron-beam fusion accelerator would enable investigators to conduct experiments with ion beams instead of electron beams. In this scheme the polarity of the diode would be reversed: the central element in each transmission line would now serve as the anode, and the outer element would be the cathode. Light ions (for example protons) would be extracted from a plasma formed on the concave face of each anode, which is designed to form a geometric focusing device located between each pair of transmission lines. The grill-like structure in front of each focusing device would set up a pulsed magnetic field to suppress the flow of electrons. Ions would pass through magnetic-field coils and would be focused to enter an array of plasma discharge channels.

tion data necessary for the design of the new machine.

The new Sandia electron-beam fusion accelerator will initially consist of 36 modules delivering a total of 30 trillion watts; it will be constructed to make possible its upgrading to at least 60 trillion watts. The assembly of the accelerator began this past summer, and pulsed-power testing should start late next year. If these early steps are successful, the upgrading could be completed as soon as 1983, making it possible to conduct pellet-ignition experiments by 1985. If these latter steps also prove successful, then the inherent simplicity and efficiency of the particle-beam technique will clearly set the stage for future reactor applications.

For this technology to proceed beyond the demonstration of scientific feasibility to the power-reactor stage it will be necessary to demonstrate the components for repetitively pulsed accelerators capable of operating for at least a year (almost a billion pulses) with little or no maintenance. This will mean that components such as advanced gas-cooled spark-gap switches and high-voltage transformers are likely to be needed rather than the components developed for the earlier single-pulse applications. A developmental program at Sandia aimed at the solution of these problems recently resulted in the demonstration of a generator operating at 100 pulses per second with an average power of 30,000 watts and a peak power of 10 billion watts. This technology is one of the least developed aspects of pulsed power, and providing its feasibility will call for substantial investments in time and money. We believe an accelerator with an average power of a million watts might be demonstrated as early as 1985. If scientific feasibility is shown by then, we would be able to propose the next step: a small experimental power reactor with an average power of 10 million watts.

In our longer-term studies we have been considering a small power reactor that would have a reactor chamber less than three meters in radius. The reactor would operate at 100 million watts of electric power and would require a pellet energy gain as small as 30. Such small units could achieve a high degree of flexibility in future sizing, siting and installation of power reactors. In studies conducted by the Bechtel Power Corporation a trillion-watt reactor driven by electron beams is being considered; this machine would be based on a fission blanket (consisting of either uranium 238 or thorium 232), which would produce not only electric power but also fissionable material for conventional light-water fission reactors. In the initial Bechtel estimates it is concluded that an economically acceptable power cost could be achieved with pellet gains of 18 and a blanket gain of 5. Whether or not such a hybrid will prove to be desirable is the subject of debate. In any event the high efficiency of particle accelerators makes it possible to consider the environmentally attractive pure fusion approach with small pellet gains.

The U.S. particle-beam fusion program is proceeding at a pace comparable to the Russian program at the Kurchatov Institute, although (according to Rudakov) the State Committee on Atomic Energy of the U.S.S.R. appears to have made a stronger commitment to electron-beam fusion than to laser fusion, the opposite of the priorities set by the U.S. Department of Energy. The reasons for the Russian position appear to be purely pragmatic, based on the simplicity, scalability and lower cost of the technology rather than on specific scientific factors. The effort at the Kurchatov Institute is centered on the development of a $50-million accelerator called Angara V, which will have an energy output of 100 trillion watts when pellet experiments are scheduled to begin in 1984. The Russians are considering pellets with very high energy gains (greater than 1,000) along with a fission blanket in order to produce enough power to pay for the complex pellets and the cost of replacing the magnetically insulated transmission lines. The Russians do not plan at this time to propagate their particle beams; instead they will place the transmission lines in contact with the pellet, letting the high energy gain and production of fissionable fuel pay for the frequent replacement of damaged transmission lines. Whether this approach or the propagation technique we are pursuing ultimately prevails, it is evident that the technology is rapidly evolving for the irradiation of fuel pellets with high-current particle beams powerful enough to produce a significant output of fusion energy.

The Assembly of a Virus

The tobacco-mosaic virus is made up of a strand of nucleic acid encased in a rod of one kind of protein. The two components come together spontaneously but in a way that is unexpectedly complex

by P. Jonathan G. Butler and Aaron Klug

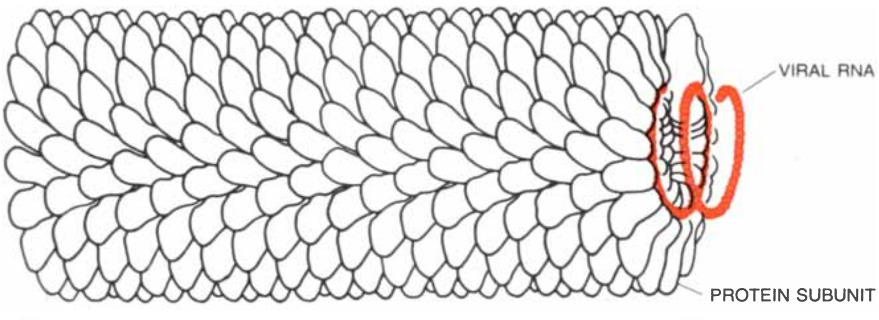
Viruses are complex particles made up of inert giant molecules: proteins and nucleic acids (DNA or RNA). They are dead in the sense that they lack any internal metabolism, but they come alive on entering the living cell. For this reason they are obligate parasites, able to reproduce only by taking over the enzymatic machinery of the host cell.

Because of their extreme simplicity viruses have proved invaluable to molecular biologists interested in the structure and function of genes. Viruses also provide a simple model of cell development, because their multiplication inside host cells involves the controlled expression of a small number of genes and the assembly of a small number of proteins into a highly ordered structure. The assembly of viruses has therefore become a paradigm for the construction of large molecular structures within living cells.

The work of our group at the Medical Research Council Laboratory of Molecular Biology in Cambridge, England, has focused on the tobacco-mosaic virus, which infects the cells of the tobacco leaf. One of the simplest and most viable viruses known, it consists of a single strand of RNA packaged within a rod of protein with a hollow center. The viral RNA is 6,400 nucleotides long and is intercalated within the turns of a closely coiled helix of 2,130 identical protein subunits, so that about three RNA nucleotides are bound to each protein subunit. The protein surrounds and isolates the RNA, protecting it from damage until the virus has successfully infected the host cell. Once the RNA is inside the cell it is released from the protein and the viral genes set to work generating large numbers of new virus particles.

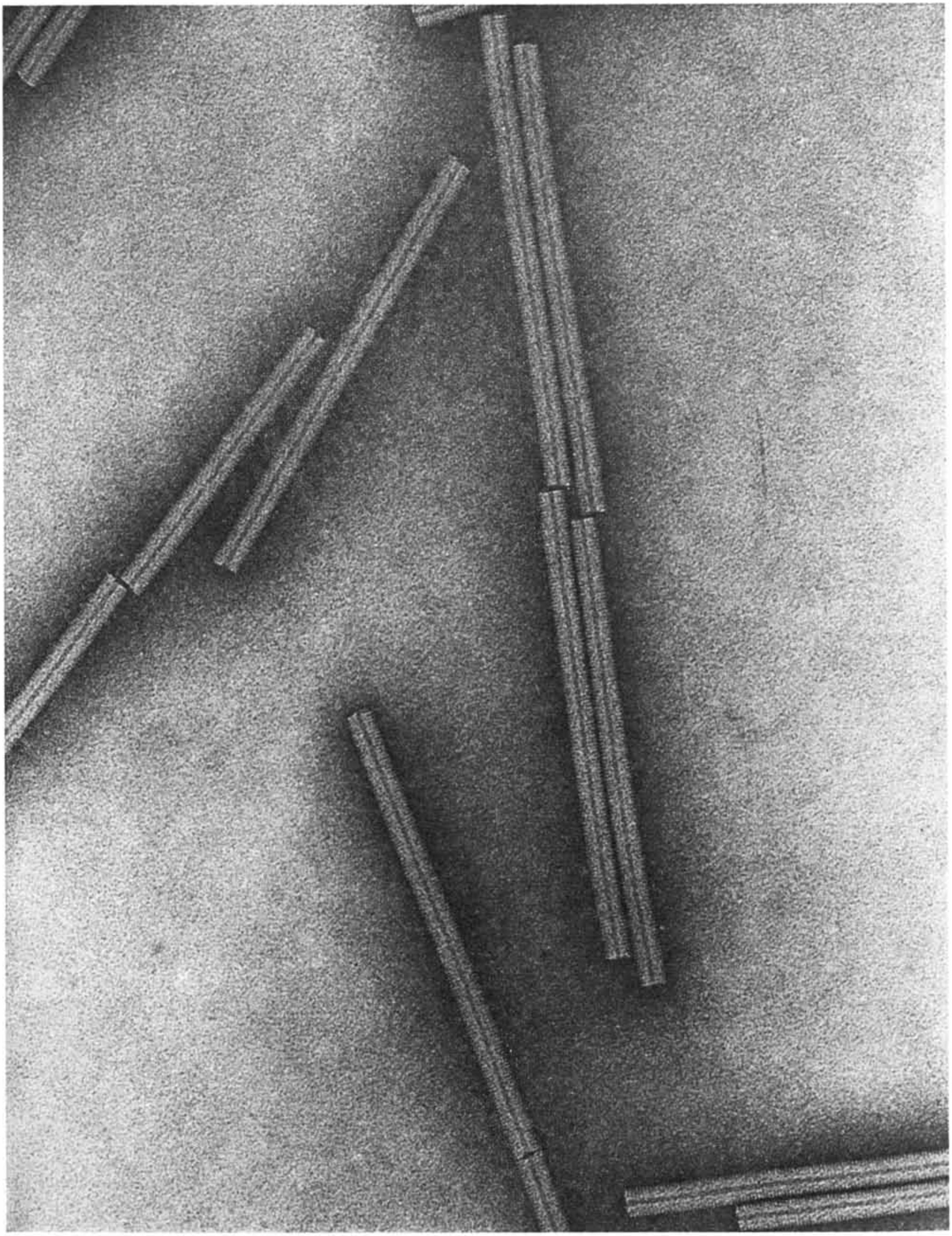
In 1955 a classic series of experiments conducted by Heinz Fraenkel-Conrat and Robley C. Williams of the University of California at Berkeley demonstrated that tobacco-mosaic virus could be reconstituted in the test tube from its isolated protein and RNA components [see "Rebuilding a Virus," by Heinz Fraenkel-Conrat; SCIENTIFIC AMERICAN, June, 1956]. On simple remixing, infectious virus particles were formed that were structurally indistinguishable from the original virus. Therefore all the information necessary for constructing the virus is inherent in its parts, which "self-assemble" spontaneously in solution.

The self-assembly of a helical structure such as a tobacco-mosaic virus may not seem particularly impressive. One can postulate that the protein subunits have a precise surface geometry so that they can assemble only in a unique way; the subunits make identical contacts with one another that are repeated over and over to yield a regular structure. According to the most obvious assembly scheme, the free RNA interacts with individual protein subunits to get the helix started. Then the subunits simply add themselves, one or a few at a time, to the "step" at the end of the growing helix, much as a crystal grows at a screw dislocation, but in this case trapping the RNA as they go along. Since both the virus particle and the RNA have distinct ends, it is also logical to expect that growth starts at one end of the RNA and proceeds toward the other. However plausible, these simple ideas are now known to be wrong. With the benefit of hindsight one can understand why the virus has adopted what at first seemed to be a puzzlingly more complex strategy.

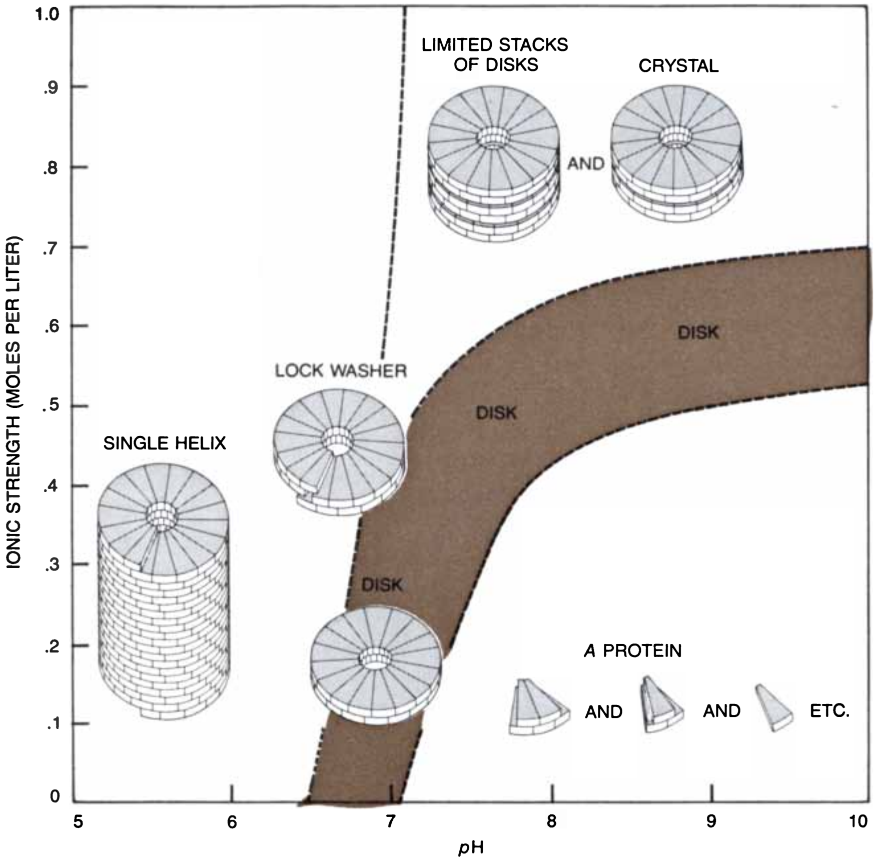


HELICAL STRUCTURE of the tobacco-mosaic virus is apparent in this drawing, which shows about a sixth of the length of the rod-shaped virus particle. The virus consists of a single long strand of RNA (*color*), representing perhaps four genes, packed between the turns of a helical protein coat made up of 2,130 identical subunits. The final length of the rod is determined by the length of the RNA. Until the virus infects its host cell the protein helix protects the RNA from damage; after infection the RNA is released from the protein and the viral genes are expressed by the host's enzymes. Central hole in the rod of the virus particle, once thought to be a trivial consequence of protein packing, plays an essential role in assembly of the virus.

The early reconstitution experiments appeared to have many features in common with the natural assembly process. The artificial reassembly of tobacco-mosaic virus from its protein and RNA components proceeded only at room temperature and at neutral *p*H, conditions similar to those found in the cells of the host plant. Moreover, reassembly was quite specific: it proceeded most readily with RNA from the same strain of the virus or from a closely related strain but poorly or not at all with other natural RNA's or synthetic RNA's. The only puzzling aspect of the reassembly process was its low rate: six hours or more were required to get maximum yields of assembled virus particles. That period of time seemed too long for the normal assembly of the virus, because the viral RNA is protected



ROD-SHAPED PARTICLES of tobacco-mosaic virus are magnified some 300,000 diameters in this electron micrograph made by John T. Finch of the Medical Research Council Laboratory of Molecular Biology in Cambridge, England. The virus "self-assembles" spontaneously in the test tube from its constituent RNA molecule and protein subunits, giving rise to infective virus particles indistinguishable from those found in nature. The assembly of the virus provides a model for how large structures are built within living cells.



PROTEIN SUBUNITS AGGREGATE in different forms depending on the *p*H (the concentration of protons, or hydrogen ions) and the ionic strength (the concentration of salt) of the surrounding medium. Individual protein subunits are found only under conditions of very low ionic strength and strong alkalinity (*p*H 10). Under less alkaline conditions (*p*H 8) clusters of three or more subunits appear. In a neutral solution (*p*H 7), similar to the condition found in the host cell, the subunits arrange themselves in flat disks consisting of 34 subunits in two rings. If the solution is made acidic (about *p*H 6.5), the protein forms long helixes devoid of RNA. At neutral *p*H, however, the helixes assemble only when the viral RNA is present. The "lock washer" consisting of a single disk is an intermediate form that arises as disks convert into helixes.

from damage only when it is completely surrounded by protein.

The assembly of any large aggregate of identical subunits, such as a crystal, can be considered in two stages: nucleation and growth, or in the case of the tobacco-mosaic virus, initiation and elongation. The rate-limiting step in the assembly of the virus, as it is in most other instances, is initiation. Because of the large number of protein subunits per turn of the helix ($16\frac{1}{3}$) about 18 separate subunits would have to bind to the flexible RNA molecule before the assembling structure could close on itself and become more than a linear aggregate of protein along the RNA. The difficulty could be avoided if some kind of jig were available on which the first few turns of the viral helix could assemble until it grew large enough to be stable.

The solution to the problem was found to lie in an intriguing observation: the coat protein by itself, free of the viral RNA, can aggregate in a number of distinct yet related forms rather than only in a helix. Donald L. D. Caspar of Brandeis University foresaw that some of the forms might provide clues to the way the virus assembles. The various aggregation states were first examined in detail by our group (including Anthony C. H. Durham and John T. Finch), and other workers have since contributed to the picture. Although there is some disagreement about the details, the broad outline is now clear: the coat protein is so designed that it knows not only where it is going (into the viral helix) but also how to get there.

The dominant factor controlling the state of aggregation of the coat protein is the *p*H of the surrounding medium (the negative logarithm of the medium's concentration of free protons, or hydrogen ions). In a slightly alkaline solution (above *p*H 7) the coat protein tends to exist as a mixture of small aggregates of several subunits; this mixture is referred to as *A* protein. Near neutrality (*p*H 7) a different and specific structure appears: disks consisting of two layers of subunits. Each layer is a ring of 17 subunits, which is nearly the same number of subunits as there are in one turn of the viral helix. At conditions like those expected within the host cell as much as 80 percent of the coat protein is incorporated into disks; the rest is *A* protein. Making the solution abruptly more acidic (down to *p*H 5) converts the disks directly into short helical "lock washers" of just over two turns in length; the lock washers then stack in imperfect register and eventually anneal to yield helixes of indefinite length that are structurally very similar to the virus particle except that they are devoid of viral RNA.

The disk aggregate of the coat protein has a number of significant properties. It is the dominant form of the protein under conditions that are known to be optimal for the reassembly of the virus in the test tube and that are plausible for its natural assembly in the host cell. Moreover, the size and structure of the disk suggest that it might be ideal to act as the jig for the initiation of virus assembly. On the hypothesis that the disk might serve as a nucleating center, we looked at its effect on the reassembly reaction. The results were dramatic. Complete virus particles were formed within 10 minutes rather than the six hours that had been required for reconstitution experiments in which the protein was in disaggregated form. We reasoned that if the disks were needed for initiation, much of this time would be spent waiting for the disaggregated subunits to assemble spontaneously into disks before the growth of the virus particles could begin.

The notion that disks are involved in the natural biological process of initiation was strengthened by experiments in which assembly was carried out with RNA's from different sources. We found that the disks interacted much more readily with tobacco-mosaic RNA than with foreign or synthetic RNA's, ensuring that only the viral RNA was picked out for being coated with the viral protein. The structure of the disk allows up to a complete turn of RNA to bind to it during the first step, so that it clearly provides for a much greater discrimination than three nucleotides binding to a single protein subunit could.

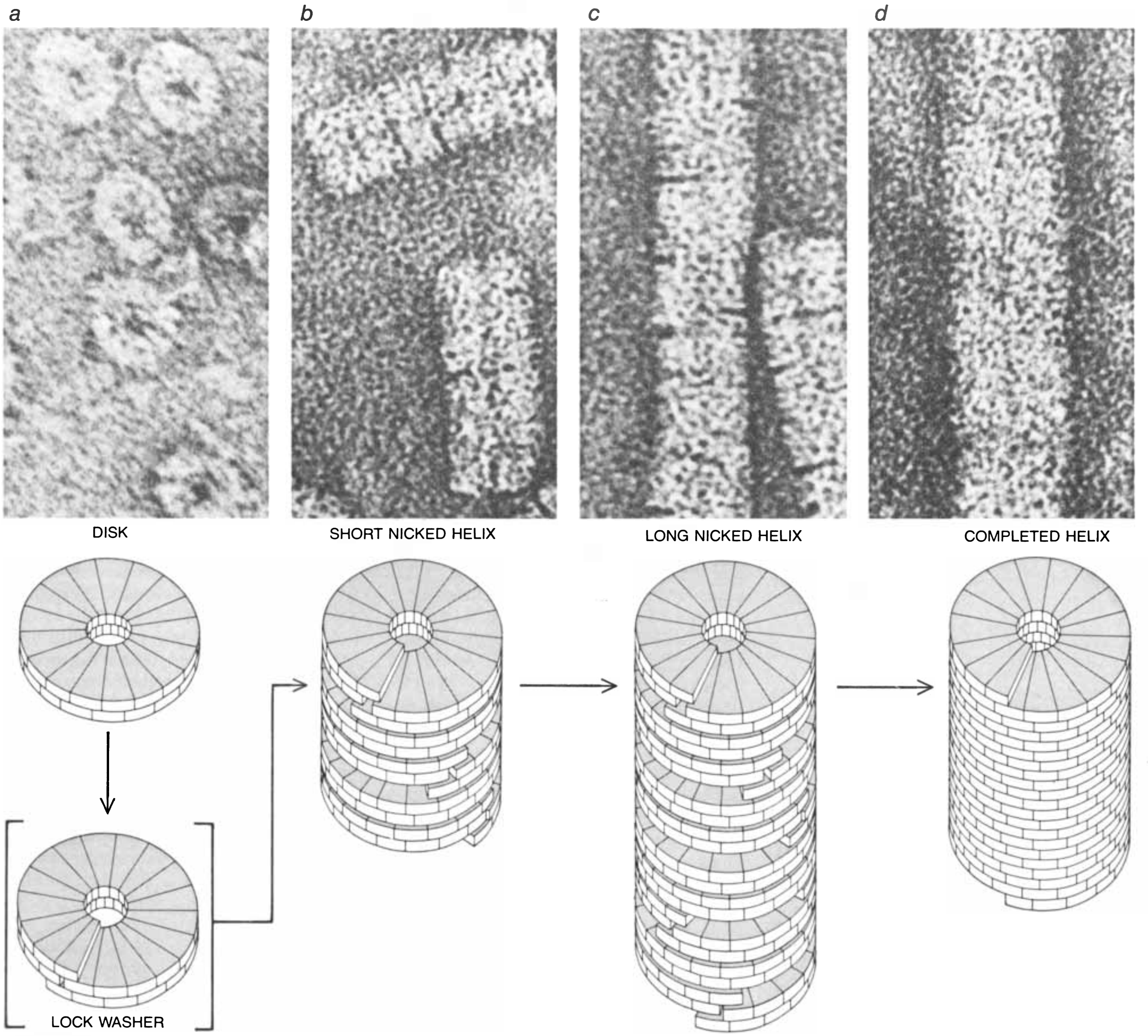
Specificity also calls for a unique sequence of nucleotides in the viral RNA that interacts strongly with the protein disk. This sequence must be a significant stretch of the RNA in order to account for the high selectivity observed; about 50 nucleotides can interact with the 17 protein subunits in one turn of the first disk. We therefore set about isolating the initiation region of the RNA by supplying just enough coat protein to allow initiation but not growth and then digesting away the uncoated ends of the

RNA with an enzyme. Together with our colleague David Zimmern we found we could isolate a series of RNA fragments, all of which contained a common core sequence with variable lengths at each end. The shortest of the fragments was about 65 nucleotides long, just over the length necessary to bind to one complete turn of the disk, and we found that it bound to disks tightly and specifically. We concluded that this short fragment contains all the information necessary to specify the normal initiation reaction.

The large size and relatively low yield of the initiation region of the tobacco-mosaic RNA made determining its nucleotide sequence technically difficult. As we were working on the isolation and sequencing of this region Léon Hirth and his colleagues at the University of Strasbourg had begun to determine the sequence of nucleotides in various tobacco-mosaic RNA fragments they had isolated from uncoated viral RNA that had been partly digested by an enzyme. In this way they could obtain relatively good yields of these shorter fragments, and the determination of the nucleotide sequences was not too difficult. By chance one of their fragments overlapped the initiation region, and from our joint results it was possible to identify and complete the sequence.

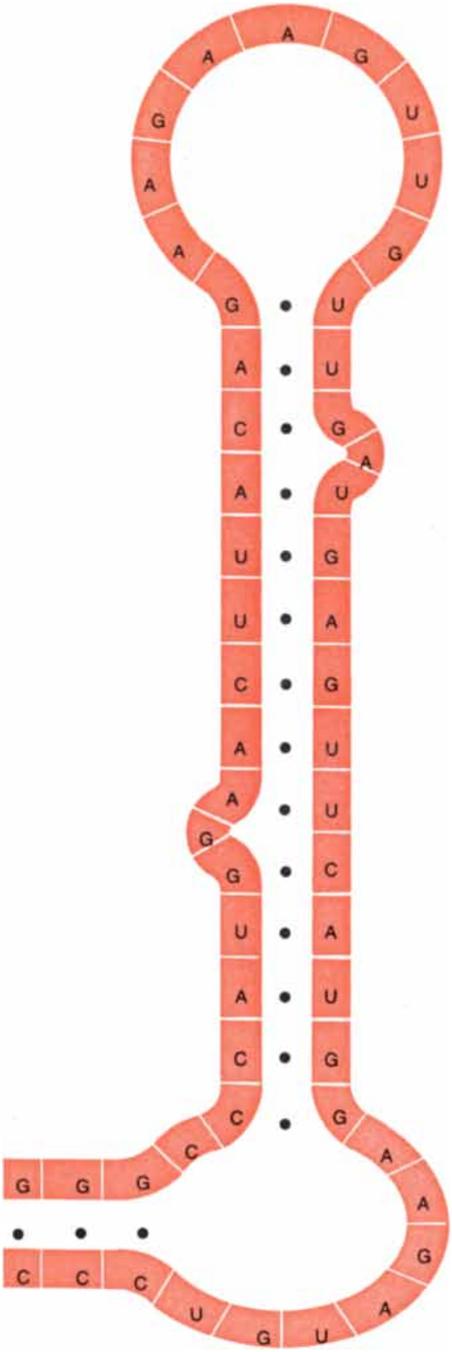
The sequence of the initiation region suggests that it has a hairpin structure: a stem consisting of a double helix with weakly paired nucleotides and at the top of the stem a loop with unpaired nucleotides. The loop and the adjacent part of the stem consist of an unusual series of nucleotide bases with a repeating triplet motif of guanine (*G*), adenine (*A*) and uracil (*U*), with guanine in every third position: *AGAAGAAGUUGUUGAUGA*. Since there are three nucleotide binding sites per protein subunit, we speculated that such a triplet pattern could lead to the recognition of the exposed RNA loop by the protein disk during the initiation process.

With the initiation region identified



TRANSFORMATION OF DISKS TO A HELIX in the absence of the viral RNA can be brought about by lowering the *p*H of the solution to stabilize the helical aggregate, as is shown in these electron micrographs made by Finch. (In the lower half of the illustration the various structures are shown diagrammatically.) If the *p*H is lowered rapidly enough, the protein disks are converted into short helixes of just over two turns (lock washers) without dissociation into subunits (*a*). Within a few minutes the lock washers stack in random vertical orientation to yield short "nicked" helixes (*b*). These short stacks slowly aggregate over a period of about 15 minutes, forming a long nicked helix (*c*). Finally the imperfections in the rods are annealed out over a further period of hours to yield finished protein helix (*d*).

and the sequence of its nucleotides known, it became possible to locate the region along the RNA strand. Again the obvious expectation—that the initiation sequence would be near one end of the RNA—turned out to be wrong. Zimmern and T. Michael A. Wilson showed that the initiation region is about a sixth of the way along the RNA, so that more than 5,000 nucleotides have to be coated in one direction along the RNA strand and about 1,000 nucleotides have to be coated in the opposite direction.



"HAIRPIN" STRUCTURE of the initiation region of the viral RNA was deduced by David Zimmern from the most probable pairing of the nucleotide bases in the RNA strand. This arrangement gives rise to a weakly bonded double-helical stem that has a loop at the top with a special sequence of bases. The loop is thought to bind to the first protein disk to begin the assembly of the virus. It has a distinctive motif of three nucleotide bases, with guanine (*G*) in the middle position and either adenine (*A*) or uracil (*U*) in outer positions.

In parallel with the RNA-sequence studies we and our colleagues investigated the detailed structure of the protein disk with X-ray-diffraction techniques. (Meanwhile Kenneth C. Holmes of the Max Planck Institute for Medical Research in Heidelberg pursued the X-ray studies on the virus itself begun by J. D. Bernal at the University of Cambridge as far back as 1936.) The disks will form three-dimensional crystals, so that the X-ray analysis is akin to ordinary protein crystallography except for the extremely large size of the repeating unit. The disk, which consists of 34 protein subunits and about 50 nucleotides and has a molecular weight of about 600,000 daltons, was the first very large structure to be examined in detail by X-ray analysis, and it has taken a dozen years for our group in Cambridge (including most recently Ann C. Bloomer, Gerard Bricogne and John N. Champness) to carry the analysis through to high resolution. The formidable technical problems were overcome only after the development by other workers in our laboratory of a special apparatus for tackling structures of this size.

The disk has a 17-fold rotational symmetry, which gave rise to redundant information in the X-ray data that could be exploited in the analysis. The structure is now known at a resolution of better than three angstrom units. (One angstrom is 10^{-7} millimeter, about the diameter of a hydrogen atom.) The X-ray analysis yields a map of the density of the electrons in the protein disk, and we have interpreted the electron-density map to get a detailed atomic model for the coat protein. The individual interactions between the amino acids in the protein and the nucleotides in the viral RNA have not yet been deduced. Even at the stage of five-angstrom resolution we reached a few years ago, however, the structure had important consequences for our understanding of the virus-assembly process.

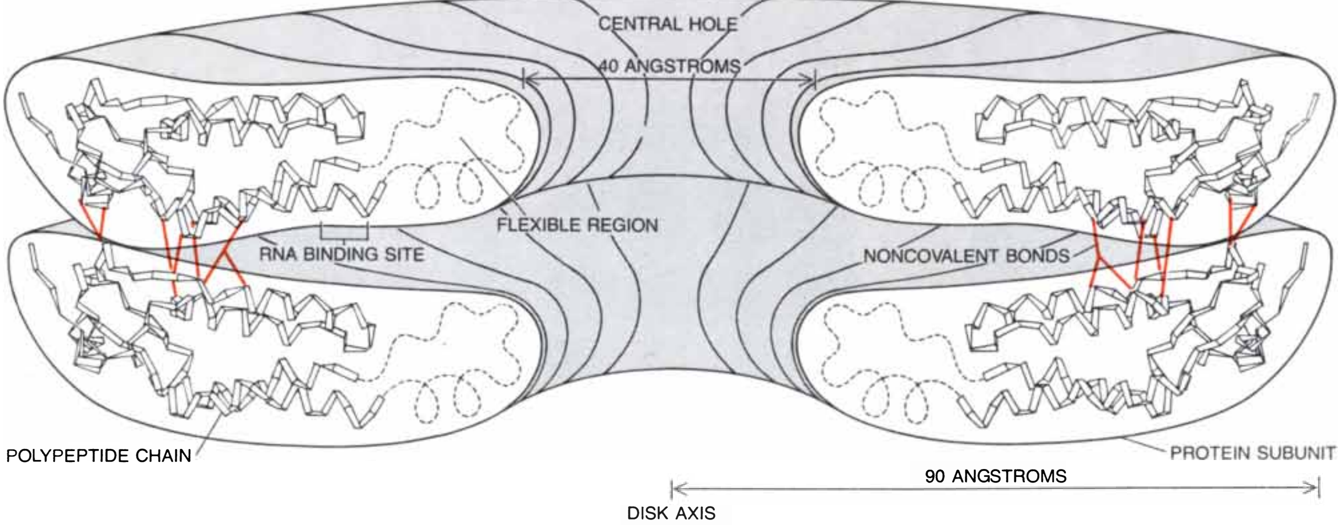
In the protein disk the subunits of the upper ring are almost flat, whereas those of the lower ring are tilted downward toward the center, so that the two rings touch only at the outer part of the disk and open toward the center like a pair of jaws. This geometry is further accentuated by the flexibility of the chain of amino acids in the region of the protein inward from the RNA binding site; in this region the chain is disordered and not tightly packed into a regular structure. When the disk is converted into the viral helix, however, the subunits from both rings tilt upward toward the center until they are all at the same angle, with adjacent turns parallel and in tight contact. The inner regions of the subunits pack together tightly, assuming a definite structure and completely enclosing and protecting the viral RNA. The structural transition therefore closes the jaws of the disk, with the RNA trapped inside.

At this stage the efforts to determine the sequence of nucleotides in the viral RNA and to elucidate the structure of the protein disk by X-ray analysis drew together. We considered the structure of the disk and how the hairpin-shaped initiation region of the viral RNA might interact with it to trigger its conversion to the helical lock-washer form. With Zimmern we proposed a hypothesis for initiation in which the RNA hairpin inserts itself through the central hole of the disk into the jaws between the rings of subunits. (The dimensions of the disk and of the RNA hairpin are right for this process.) The nucleotides in the double-helical stem then unpair, and the stem opens out as more of the RNA is bound within the jaws of the disk. Some still unknown feature of this interaction then causes the disk to transform into the lock-washer form, trapping the RNA within the rings of protein subunits as the jaws close.

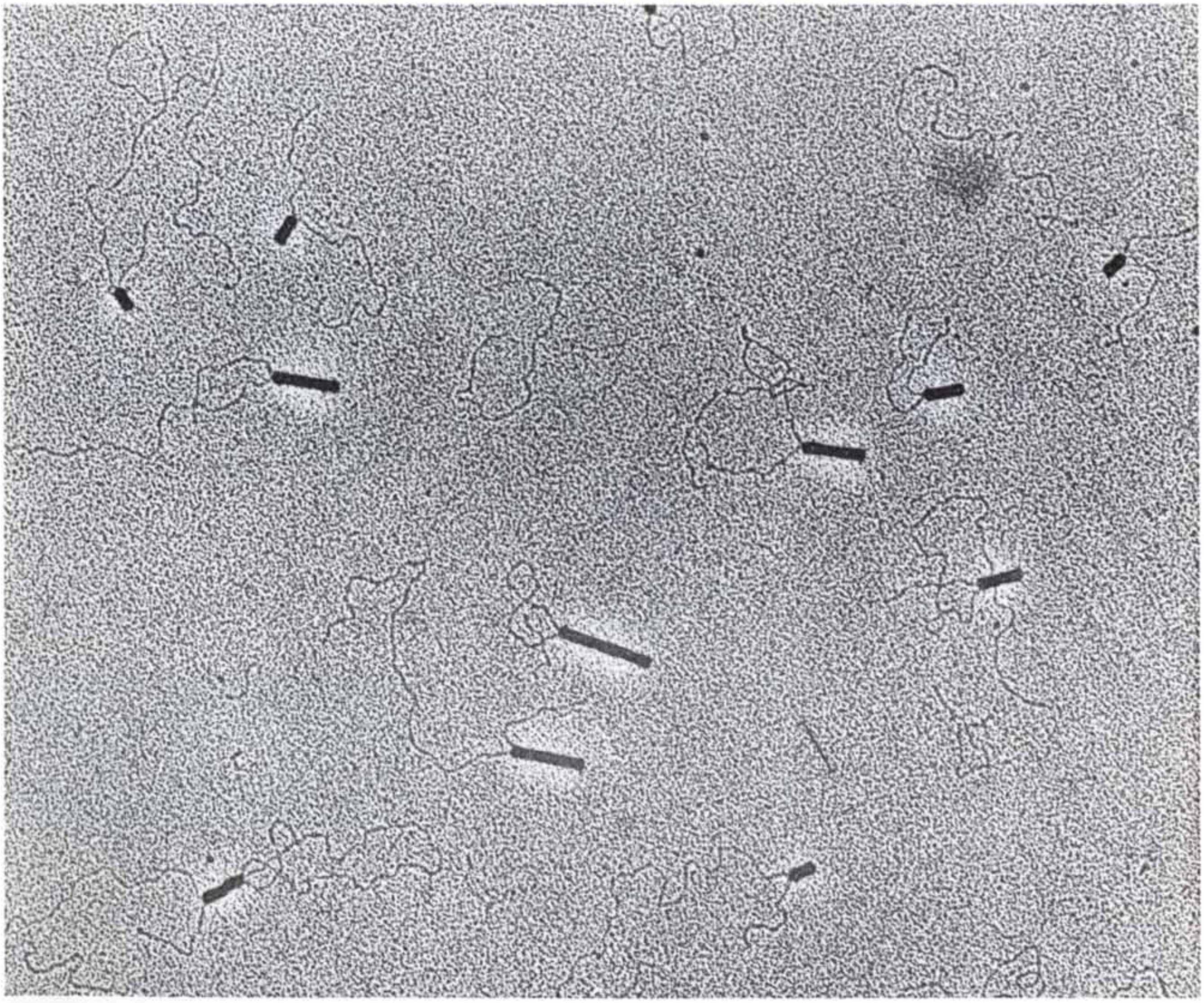
Our hypothesis about the mechanism of initiation led to a prediction that could be tested experimentally. If an RNA loop is inserted into the center of the initiating protein disk, both "tails," that is, projecting ends, of the RNA should be associated with the end of the rod-shaped virus particle from which growth began. Moreover, we expected that the shorter tail would project out directly and that the longer one (along which most of the elongation occurs) would be doubled back down the central hole of the virus. These predictions have now been confirmed. Hirth's group in Strasbourg has obtained electron micrographs of virus particles in which the two RNA tails can be seen projecting from one end of many of the rods [*see bottom illustration on opposite page*].

In Cambridge we have utilized high-resolution electron microscopy, with which the two ends of the virus particle can be distinguished, to confirm that the longer tail of the RNA is indeed doubled back through the growing rod. Moreover, we prepared virus particles with the longer RNA tail free by making the *p*H of the solution alkaline, thereby stripping protein from one end of the assembled particles; then the longer RNA tail extended directly out from the particle rather than being doubled back through the central hole. The partly stripped rods grew at less than a tenth the rate of the partly assembled rods, demonstrating the importance of the loop geometry.

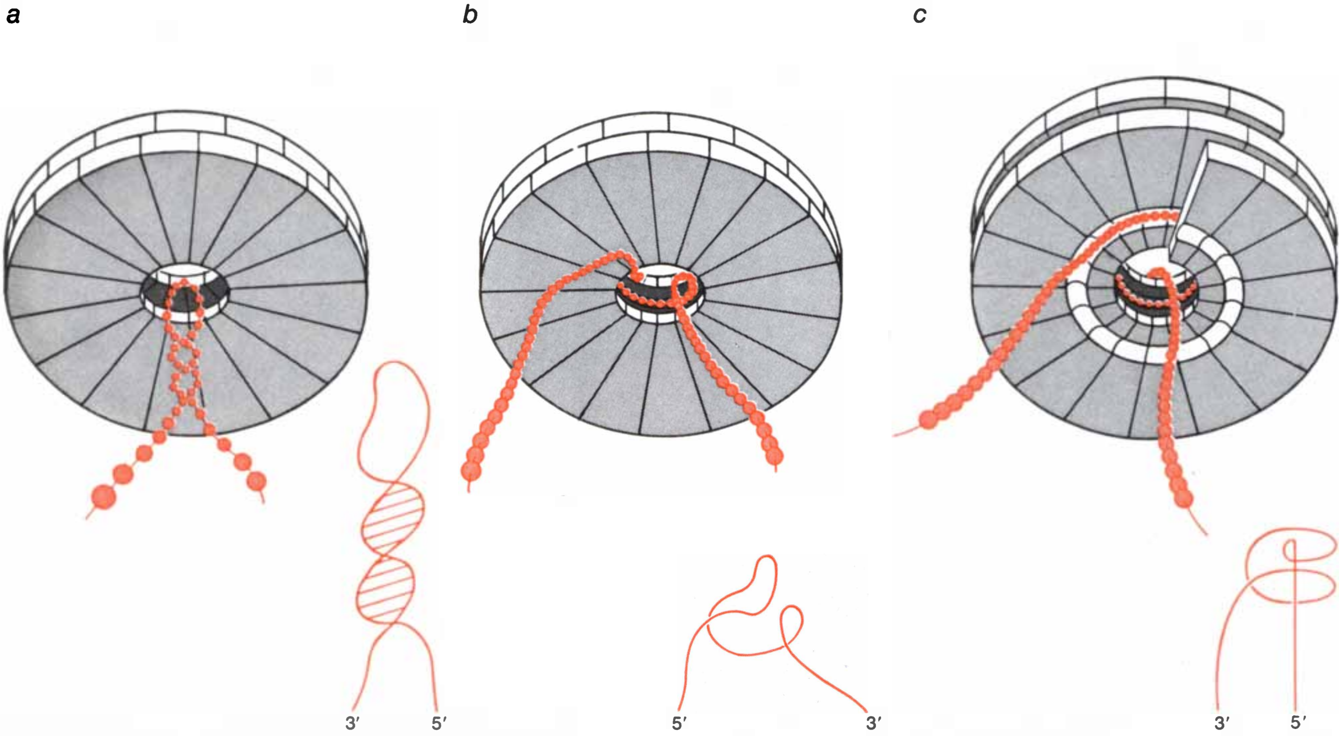
Our model of initiation has an important consequence. The special configu-



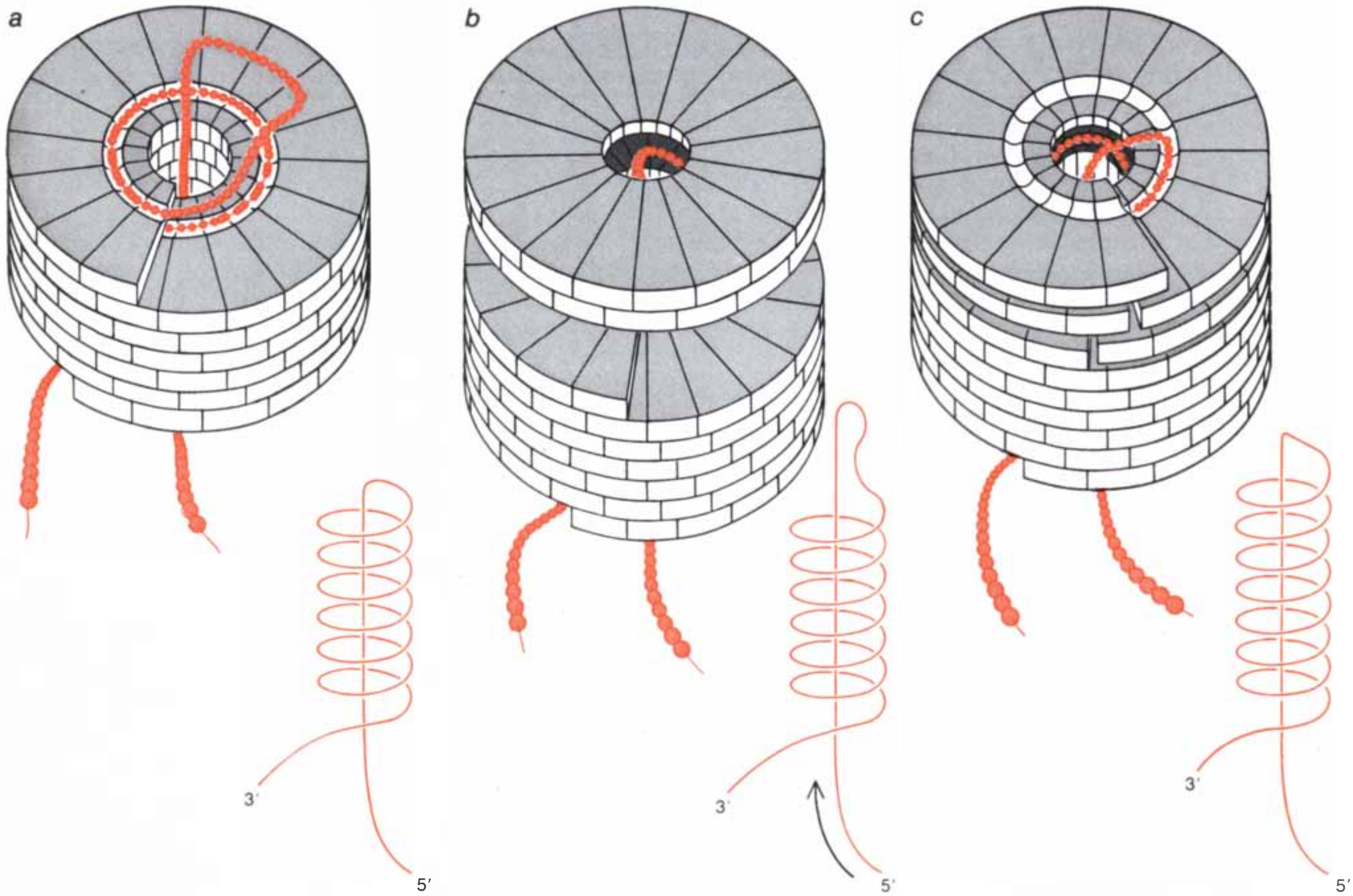
CROSS SECTION THROUGH A DISK was reconstructed from the results of an X-ray-diffraction analysis to a resolution of 2.8 angstrom units. Bent ribbons indicate the polypeptide chains that make up the protein subunits. The two-layered structure of the disk is evident: the subunits of the two stacked rings touch over a small area near the outer rim of the disk but open up toward the center like a pair of jaws. During the assembly of the virus the viral RNA binds within the jaws. The broken lines indicate the flexible portion of the protein chains extending in from the RNA binding site. Because this chain segment is in constant motion its structure cannot be resolved.



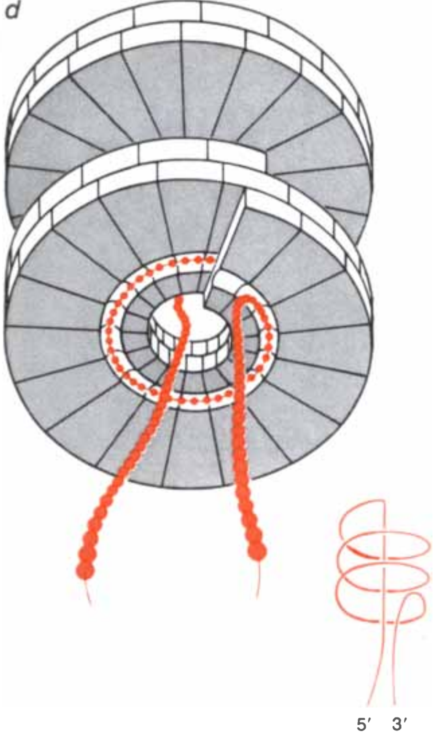
GROWING VIRUS PARTICLES have two RNA "tails" at one end, as is shown in this electron micrograph made by Geneviève Lebeurier of the University of Strasbourg. Other evidence indicates that the shorter RNA tail extends out directly from the particle, whereas the longer tail is doubled back inside the hollow core of the particle. The virus elongates primarily at the end of the particle opposite the tails.



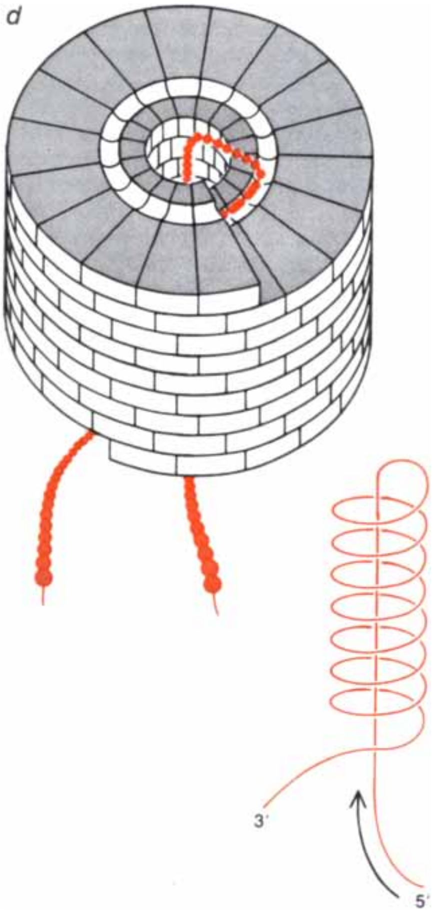
NUCLEATION of the tobacco-mosaic virus begins with the insertion of the hairpin loop formed by the initiation region of the viral RNA into the central hole of the protein disk (*a*). The loop intercalates between the two layers of subunits and binds around the first turn of the disk, opening up the base-paired stem as it does so (*b*). Some feature of the interaction causes the disk to dislocate into the helical lock-washer form (*c*). This structural transformation closes the jaws made by the rings of subunits, trapping the viral RNA inside



ELONGATION of the virus also proceeds by the addition of protein disks. As a result of the mode of initiation the longer RNA tail is doubled back through the central hole of the growing rod, forming a traveling loop at the growing end of the particle (*a*). The loop inserts itself into the center of an incoming disk and binds within open jaws of the rings (*b*). This interaction converts the new disk into a helical lock



(*d*). The lock-washer-RNA complex provides the start of the helix. Additional disks then add rapidly to the nucleating complex, so that the helix elongates to a minimum stable length.



washer (*c*). The transformed disk then stacks onto the rod, providing two turns of helix (*d*). Process repeats until assembly is complete.

ration generated by the insertion of the RNA loop into the central hole of the initiating disk could subsequently be repeated during the addition of further disks on top of the growing helix; the loop could be perpetuated by drawing more of the longer tail of the RNA up through the central hole of the growing virus-particle rod. Hence the particle could elongate by a mechanism similar to initiation, only now instead of the specific initiation loop there would be a traveling loop of RNA at the main growing end of the virus particle. This loop would insert itself into the central hole of the next incoming disk, causing its conversion to the lock-washer form and continuing the growth of the virus particle. The helical geometry of the growing rod would tend to facilitate the conversion, so that elongation would be quite rapid. Apart from the obvious advantage of delivering a package of 34 subunits at a time rather than individual ones, this mode of coating the RNA would be less affected by unfavorable nucleotide sequences than the binding of individual subunits would be.

In the elongation of the virus particle there is no obvious requirement for specific nucleotide sequences, and indeed the protein must be able to coat any sequence of nucleotides that occurs in the RNA. As the longer RNA tail is being rapidly coated with protein, the virus-particle rod must also elongate along the shorter RNA tail at the opposite end of the rod to yield the complete particle. Growth in the direction of the shorter tail of the RNA is known to be slower than that in the direction of the longer tail, but as yet little is known about how it proceeds.

There is now direct evidence that the tobacco-mosaic virus grows mainly by the addition of entire blocks of subunits in the form of disks rather than by the addition of individual subunits. In recent experiments with George P. Lomonossoff we looked at the length of viral RNA in partly assembled rods that was protected against enzymatic digestion. It turns out that the RNA is protected in steps of 50 or 100 nucleotides, corresponding to one or two turns of the RNA in the viral helix. When growth is well established, the step size tends to be 100 nucleotides, the amount of RNA associated with a single protein disk. These findings point firmly to the conclusion that the disk aggregate is involved not only in the virus's initiation but also in its elongation.

What prevents the protein disks from forming a helix devoid of the viral RNA under normal conditions? As we have seen, the aggregation of the protein subunits is controlled by the *p*H of the surrounding solution. This control appears to be achieved through the presence on each subunit of chemical groups that bind protons, such as two closely spaced carboxyl groups (COOH). At the *p*H of the host cell one of these groups in the disk is ionized (negatively); in the helical lock-washer form both are ionized. The disk form is therefore favored because of the electrostatic repulsion between the two negatively charged groups. When the viral RNA is present, however, it binds to the protein disk, providing enough free energy to overcome the electrostatic repulsion in the lock-washer form. In this way the carboxyl groups act as a negative switch to block the formation of the protein helix in the absence of the viral RNA. Moreover, only the viral RNA is coated, because it alone has the specific initiation sequence that can start the process of assembly by converting the first protein disk into the lock washer.

We have seen that the special properties of the protein disk are the key to the mechanism by which the tobacco-mosaic virus is assembled. Indeed, one might say that the protein subunit is designed to form not an endless helix but a closed two-layer variant of it—the disk—that is stable but can be converted into a helical form. The disk therefore represents an intermediate subassembly whereby the thermodynamically difficult task of initiating helical growth is overcome. At the same time the protein disk furnishes a mechanism for the recognition of the viral RNA (and the rejection of foreign RNA's) by providing a long stretch of sites that interact with a specific sequence of RNA nucleotides. In short, as an obligatory intermediate in the assembly of the tobacco-mosaic virus, the protein disk simultaneously fulfills the physical requirement for initiating the growth of the RNA-protein helix and the biological requirement for specifically recognizing the viral RNA.

The development of the disk aggregate of the coat protein and the hairpin configuration of the RNA for initiating the viral helix was apparently too good a system to abandon in favor of subsequent elongation by the addition of single subunits. The protein disks therefore participate in the growth of the helix in the principal direction of elongation. On the other hand, the virus particle must also be disassembled in order to liberate the viral RNA in the infection of the host cell. The disassembly is probably accomplished by the sequential removal of individual subunits from one end of the virus particle. Therefore the construction of the virus is not left to the driving power of an unbalanced biochemical equilibrium, as it would be if assembly and disassembly were simple reversals of each other. Instead an intricate structural mechanism has evolved to give the process an efficiency and certainty whose basis is now understood.

The Optics of Long-Wavelength X Rays

The X rays of crystallography and medical radiography are "hard," or short-wavelength. The "soft," or long-wavelength, X rays are being examined for microscopy, astronomy and microelectronics

by Eberhard Spiller and Ralph Feder

Between ultraviolet radiation and short-wavelength X rays lies a once neglected region of the electromagnetic spectrum: the "soft," or long-wavelength, X rays. Until the past decade physicists had worked little with this radiation, primarily because it was difficult to generate in the laboratory. The "hard," or short-wavelength, X rays, on the other hand, are easily generated, and for more than six decades their scattering characteristics and penetrating power have been exploited to examine the nature of matter and the interior of the human body. The technique of X-ray crystallography has contributed much to the understanding of the atomic structure of solids. When hard X rays strike a crystal, they are diffracted, or scattered, in a decipherable way that can reveal the geometric pattern of the atoms of the crystal. It is also the hard X rays that have made possible medical radiology.

Over the past 10 years an unexpected source of soft X rays, intense enough for any conceivable application, has been provided by synchrotron particle accelerators. When electrons race around the circular track of a synchrotron at speeds close to the speed of light, they emit soft X rays in abundance. Soft X rays have proved to be useful in analyzing the structure of objects that range in size from the chromosome of the living cell to the hot plasma in fusion experiments to the corona of the sun. (In the last two cases, of course, the X rays are generated by the phenomena being observed.) These applications depend on how matter absorbs and emits soft X rays. The absorption of soft X rays is also the key to the new technology of X-ray lithography, in which microelectronic circuits are laid down on semiconductor "chips" with a density potentially more than two orders of magnitude higher than that achieved by conventional methods.

The principal mechanism by which matter absorbs X rays is the photoelectric effect. When an X-ray photon collides with an atom, it will liberate one of the atom's electrons if its energy is high enough to overcome the electron's binding energy. Each electron in an atom has a different binding energy, and the energy is greatest for the electrons that are closest to the positively charged nucleus of the atom.

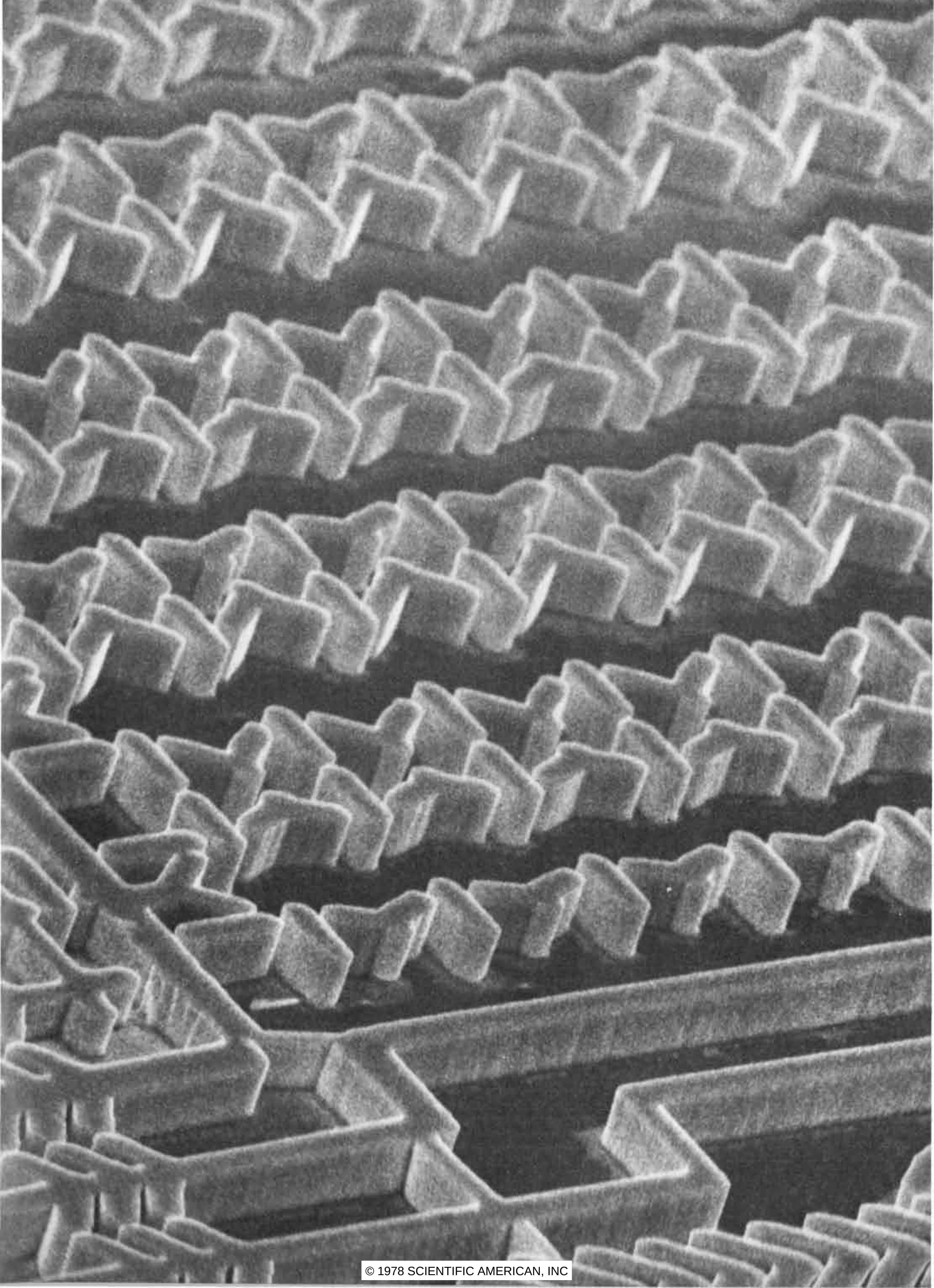
The fact that each kind of atom has its own absorption characteristics, corresponding to the binding energies unique to its electrons, makes it possible to determine the composition of unknown substances by bombarding them with X rays and recording the energies at which the waves are sharply attenuated [*see top illustration on page 74*]. The attenuation of light waves as they pass through a material is characterized by the quantity called the absorption length, which for a particular wavelength is the thickness of material that will attenuate the radiation to 37 percent of its incident intensity. For visible light different materials span a huge range of absorption lengths. In most metals light waves will be completely attenuated in less than 1,000 angstrom units. (An angstrom unit is 10^{-7} millimeter.) In some glasses light waves would not be much attenuated in several miles of the material.

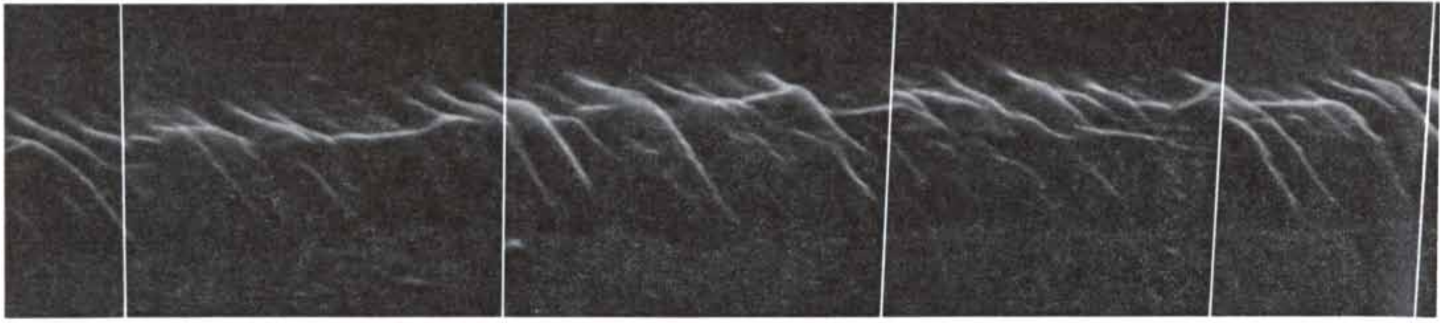
Wavelength is inversely proportional to energy, and so short-wavelength X rays are more energetic than long-wavelength ones. In many instances the short waves are too energetic to strongly interact with the electrons in a material; they pass right through the material unaffected by local variations in its atomic structure. The longer waves, on the other hand, have energies that more often correspond to those of the electrons. From the fine details in the absorption spectrum of soft X rays it has been possible to calculate the distance between the atoms and molecules in solids and liquids to an accuracy of about .01 angstrom.

For years physicists have wanted to construct an X-ray microscope that would exploit the ability of soft X rays to detect small structures. The need for such an instrument is clear. The resolution of light microscopes is limited by the comparatively long wavelength of visible light. And transmission electron microscopes, although they have a much higher resolution, are weak in penetrating power and are therefore limited to very thin specimens. Moreover, in transmission electron microscopy the specimen is usually stained and mounted in a vacuum chamber. Such preparation, which alters biological material, would not be required in X-ray microscopy. The difficulties in constructing an X-ray microscope, however, have proved formidable, because X rays cannot easily be brought together to form an image.

Although lenses can focus visible light, they cannot focus X rays. When the waves of electromagnetic radiation such as light or X rays pass through a material, they propagate at speeds different from their speeds in a vacuum or in air and hence they are refracted, or bent. The degree of refraction depends both on the wavelength of the radiation and on the nature of the material. For visible light traveling through the glass of lenses and prisms the effect is strong enough to focus the light waves by retarding and refracting the wave fronts so that they all meet at one point. For ex-

MICROELECTRONIC CIRCUIT, magnified 4,690 times in the scanning electron micrograph on the opposite page, was fabricated by X-ray lithography. The circuit, a magnetic-bubble pattern, was formed by directing soft X rays at an X-ray-sensitive polymer through a gold mask. Here the circuit lines are one micrometer wide and about three micrometers high. The ability of X-ray lithography to produce lines with high relief is an advantage of the technique.





X-RAY REPLICA of a chromosome of the fruit fly *Drosophila* was made by placing the material on an X-ray-sensitive polymer and exposing it to soft X rays (wavelength 44.8 angstrom units). The X rays were attenuated according to the type of material in the chromo-

ample, a spherical wave diverging from a point source of light can be transformed by a lens into another spherical wave converging to an image point. The lens retards the wave fronts passing through its center more than the wave fronts passing through its edges in such a way that the time it takes for the wave fronts to travel from the object to the image is the same for all possible trajectories. For soft X rays, as opposed to visible light, the retarding and refracting effect of most materials is negligible. Only very thick lenses of a few materials could retard and refract soft X rays to the extent necessary to focus them. Soft X rays, however, would not be energetic enough to penetrate such thick lenses; the waves would all be absorbed before they emerged from the other side. For hard X rays, in spite of their greater penetrating power, the focusing situation is just as bad, because even the thickest lenses will hardly deflect them.

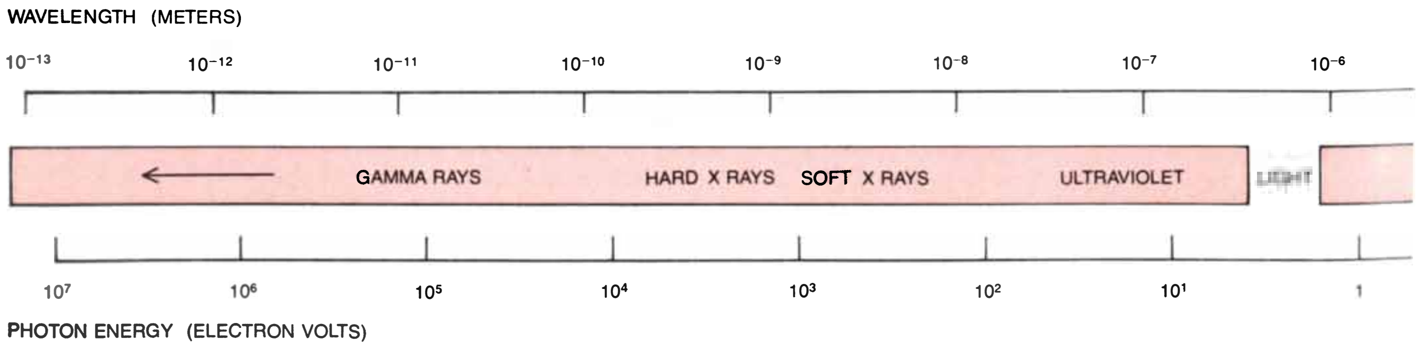
The simplest and most successful way to produce an image with X rays is with contact X-ray microscopy. This technique, which achieves a resolution substantially better than that of the light microscope, creates a shadowgraph of the specimen. The size and composition of the specimen and of its smallest features determine the wavelengths that will cast the most revealing shadows. The optimum wavelength is a compromise between maximum penetration and maximum contrast. The thickness of the specimen calls for X rays hard enough to penetrate it, but the smallest features of it call for X rays soft enough to be sufficiently absorbed and produce enough contrast. The penetration of thick objects can require a wavelength of two angstroms; the best contrast of minute features can require wavelengths of up to 100 angstroms.

Behind the specimen is a screen or film that records the intensity of the X rays that pass through it. As we have seen, the intensity will decrease sharply wherever the energy of the waves is equal to the energy needed to liberate electrons from their atoms. Such attenuation will reveal much about an object's composition. For example, the energy of X rays with a wavelength of 44.8 angstroms corresponds to the energy required to remove an inner electron from a carbon atom. If an object composed mostly of carbon is exposed to X rays with wavelengths slightly longer than 44.8 angstroms, and hence with energies too low to remove the inner electrons, the object will scarcely absorb the waves and its image will exhibit low contrast. If the same object is exposed to X rays with wavelengths equal to or slightly less than 44.8 angstroms, the object will have considerably higher absorption and its image will exhibit more contrast. The difference between the two images, one made with a wavelength just above the "absorption edge" of an element and the other made with a wavelength just below the absorption edge, would outline the distribution of the element in the object.

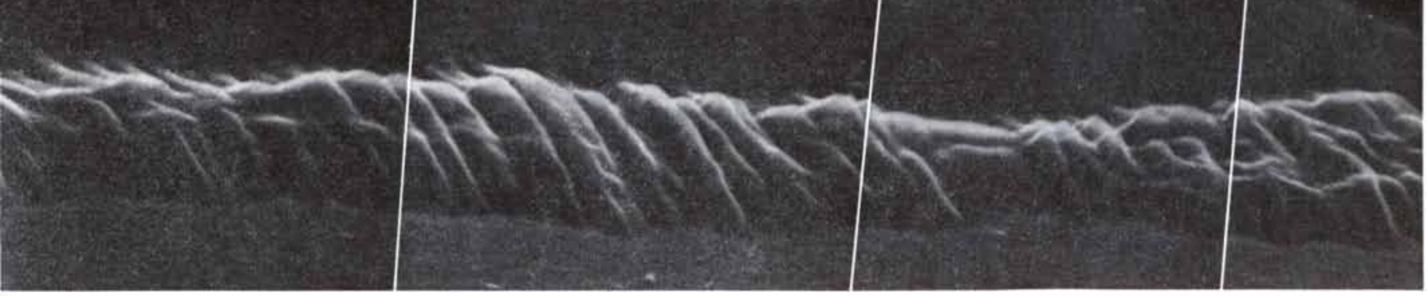
The drawback of contact X-ray microscopy is that the image is no larger than the object. Until recently after the image was recorded on photographic film it had to be viewed through the light microscope. That meant the resolution of the image was limited to the resolution obtained with visible light, a limitation X-ray microscopy was supposed to overcome. Nevertheless, such microscopy has been a useful investigative technique because of the penetration and contrast that X rays provide.

In 1972 David L. Spears and Henry I. Smith of the Lincoln Laboratory of the Massachusetts Institute of Technology modified the technique of contact X-ray microscopy so that it could be applied to the lithographic fabrication of microelectronic circuits. This X-ray process, which is still in the stage of laboratory development, can facilitate the faithful transfer of the intricate details of the circuit from the large scale to the microelectronic one. Electron-beam lithography is the only other engraving technology that can reproduce such fine details. The smallest features that conventional photolithography with ultraviolet radiation can form are limited by the wavelength of the radiation to about one micrometer (10^{-3} millimeter), although only structures as small as a few micrometers have been routinely produced. Since X rays have wavelengths that are measured in nanometers (10^{-6} millimeter), they offer the prospect of much higher resolution. Structures with dimensions of less than a tenth of a micrometer have already been made.

In X-ray lithography the microelectronic circuit is built up layer by layer on



ELECTROMAGNETIC SPECTRUM displays radiation according to its wavelength and also to the energy of its photons, the quanta of electromagnetic radiation. The wavelength and the photon energy are inversely related. X rays occupy the region between the short-wave-



some. When the polymer was put in a solvent, the areas less intensely exposed to X rays dissolved less readily than those more intensely exposed. This mosaic of pictures of the replica was made with a scanning electron microscope. The preparation was made by John Sedat.

top of a "wafer" that bears an array of chips. The process entails repetitively bathing the wafer in solvents or etchants and exposing it to radiation. The wafer is first coated with an X-ray-sensitive organic polymer called an X-ray resist. The coat is applied by placing a drop of a solution of the polymer on the wafer's surface. The wafer is then rapidly rotated, the drop spreads out and the solvent evaporates, leaving a thin, even film of resist on the surface of the wafer.

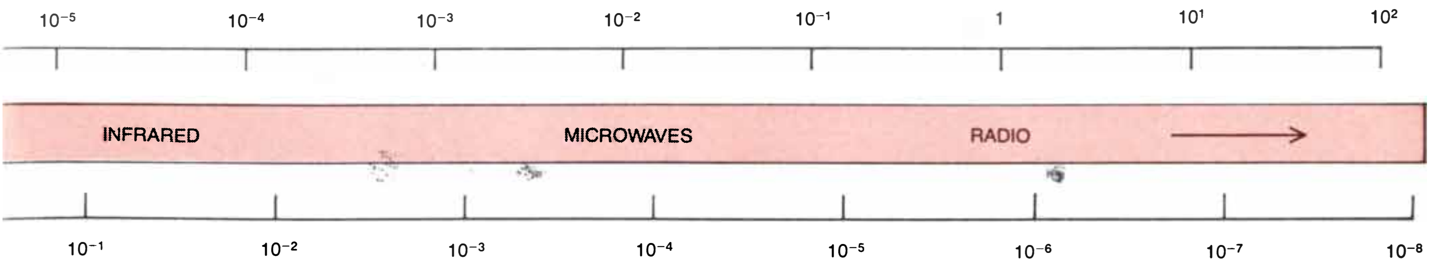
The resist-coated wafer is now exposed to X rays through a mask inscribed with the circuit design. The circuit pattern on the mask consists of a heavy material, such as gold, that absorbs a large fraction of the incident X rays; the thin substrate of the mask consists of light substances that allow most of the X rays to pass through it. In X-ray lithography the wavelength has ranged from four to 50 angstroms. Mask substrates as thick as 50 micrometers will adequately transmit X rays as short as four angstroms. Thinner substrates, although they are more difficult to work with, will transmit X rays of about 50 angstroms, which for reasons that will become apparent below are better to work with when the highest resolution is required.

The key property of an X-ray resist is that after exposure to X rays the rate at which it will dissolve in certain solvents changes. If a wafer that has been irradiated through a mask with X rays is washed in a solvent, some kinds of resist will dissolve wherever the mask was transparent. In this way the circuit design on the mask is imprinted on the resist. The last step in lithography involves transferring the circuit pattern from the resist to the wafer itself. This can be done in a number of ways. For example, when a silicon wafer is bathed in hydrofluoric acid, it is etched wherever it is not covered by the resist. As a result the pattern is etched into the wafer. The entire bathing and irradiation process must be repeated for the other layers in the circuit.

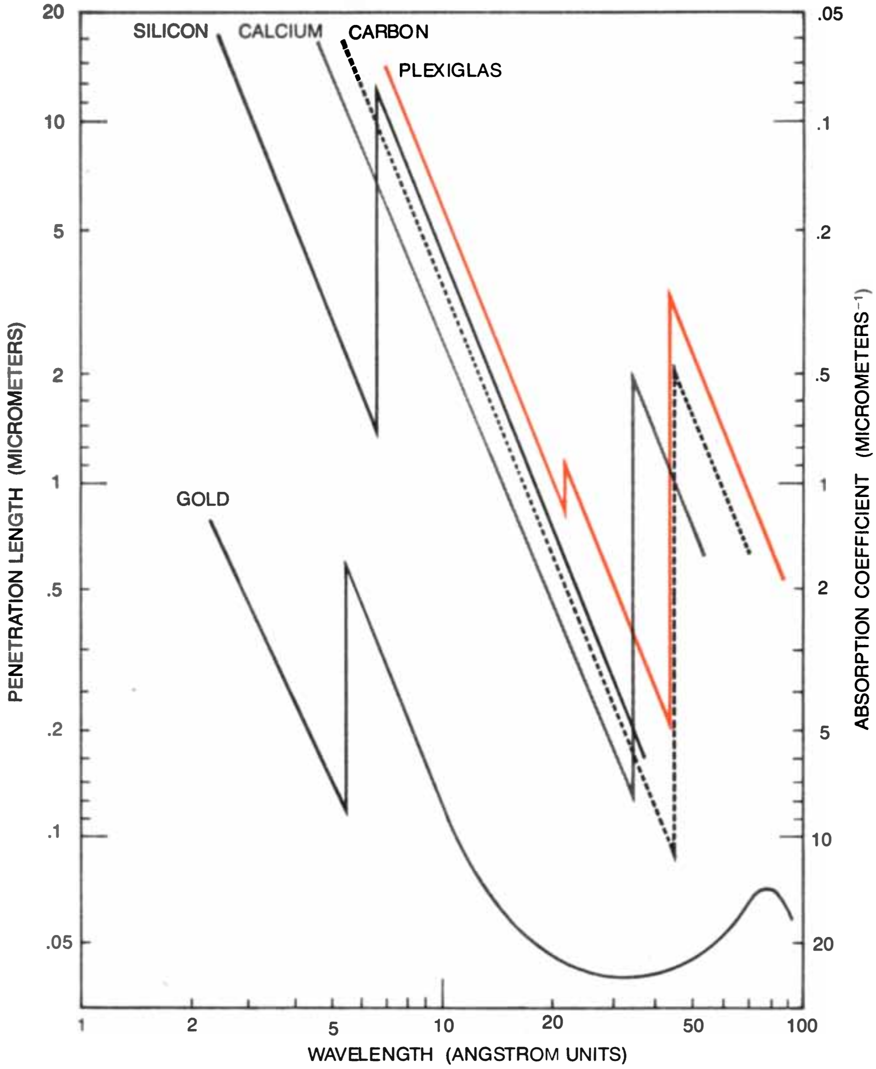
X-ray resists have turned out to be as important for contact X-ray microscopy as they have for X-ray lithography. They can be used instead of photographic film as the recording medium. A layer of resist placed behind a specimen will become more soluble at the points where the most radiation comes through. When the layer is washed in a solvent, it will selectively dissolve to form a relief image of the specimen, with the highest areas in the relief corresponding to the regions of highest absorption in the specimen. The surface topography of the developed resist image can then be inspected in the scanning electron microscope, which has a much higher resolution than the light microscope.

Polymethyl methacrylate (Plexiglas) is an X-ray resist capable of extremely high resolution: 50 angstroms for a wavelength of 50 angstroms. Shorter wavelengths cannot offer better resolution because they will affect not only the solubility of the material they strike but also that of the neighboring material. The basic reason can be given quite simply. The energetic photon of a hard X ray that has managed to pass through the specimen will penetrate the resist until it strips an electron from an atom. The removal of an electron always corresponds to a local change in the chemical properties of the resist, such as the breaking of a bond in a polymer chain. The energy the electron acquires will be more than enough to free it from the atom. In collisions with other atoms it will get rid of the excess energy by setting free additional electrons. They in turn will liberate still others, and the process will continue until the binding energy of the bound electrons in a polymer chain of the resist exceeds the energy of the free electrons.

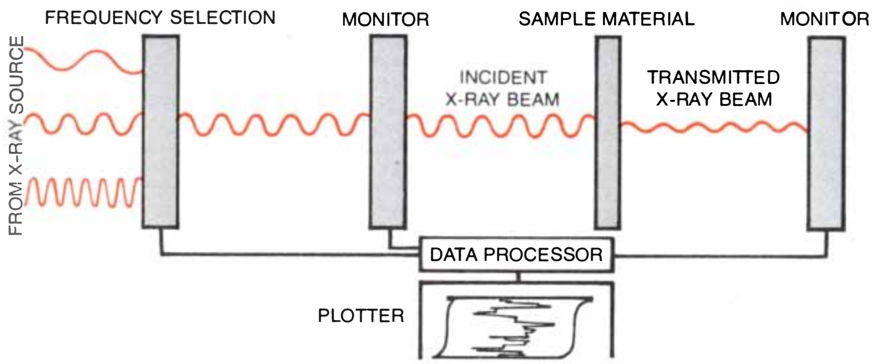
In this way the energy of a short-wavelength X-ray photon will be distributed among many electrons in the polymethyl methacrylate over a specific range around the atom that originally absorbed the X-ray photon. The energy of a soft-X-ray photon liberates considerably fewer electrons within a proportionately smaller range. This means that a hard-X-ray photon affects the solubility of a larger region of the resist than a soft-X-ray photon does, and hence a relief made with soft X rays can achieve a higher resolution. For an X-ray wavelength of 50 angstroms the resolution limit set by the range of liberated secondary electrons is of about the same dimensions: 50 angstroms. Using still longer wavelengths to decrease the range will not improve the resolution because diffraction effects will come



length ultraviolet rays and the long-wavelength gamma rays. Until recently soft X rays attracted little attention because they were difficult to generate. They can now be obtained readily from synchrotrons, and such machines are being specifically built for the purpose.



ABSORPTION SPECTRUM of soft X rays is plotted for various materials. The penetration length, measured here in micrometers, is the thickness of material that will attenuate radiation of a particular wavelength to 37 percent of its incident intensity. With increasing wavelength, and hence with decreasing energy, the penetration lengths become shorter. The absorption coefficient, which is the inverse of the penetration length, is a measure of the amount of radiation absorbed by a material. Wherever the energy of the X rays is greater than the energy needed to free electrons from their atoms there is increased absorption. Such energies will show up as absorption edges, or discontinuities, in the curves. For example, the absorption edge in the carbon spectrum at 44.8 angstroms marks the energy needed to free a carbon's inner electron.



EXPERIMENTAL SETUP for measuring the X-ray-absorption characteristics of materials is depicted in this highly schematic diagram. A beam of X rays composed of different wavelengths is first passed through a device that can be adjusted to select only X rays with a particular frequency or energy. The attenuation of X rays in passing through a material is found by comparing the intensity of the incident beam with the intensity of the transmitted beam.

into play. In other words, a resolution of 50 angstroms is the best that can be obtained with polymer X-ray resists.

Electron microscopy has a higher resolution than contact X-ray microscopy because electrons can have shorter wavelengths than soft X rays. There are nonetheless two major advantages to directing electrons at an X-ray replica of a specimen rather than at the specimen itself. First, X-ray microscopy can reveal the inner structure of a specimen, which electrons cannot easily do, and second, living specimens can be examined. The success of contact X-ray microscopy has diminished the need for an X-ray microscope that would magnify directly with X rays. The resolution that has already been obtained is close to the limit set by diffraction effects, and there is no chance an X-ray microscope with focusing elements could achieve much higher resolution.

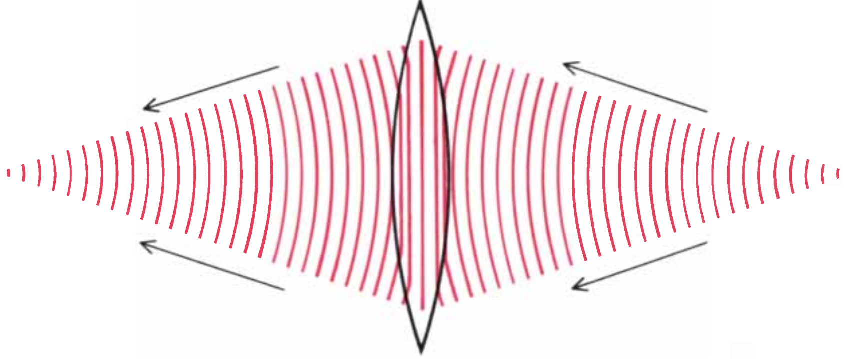
Focusing devices for X rays are still needed, but for other reasons. By making it easier to control X-ray beams, focusing elements would greatly simplify the construction of many scientific instruments. Moreover, without focusing elements it would be impossible to make X-ray observations in astronomy. Focusing devices would be beneficial even for X-ray microscopy because they would reduce the amount of radiation that needs to be sent through the specimen. Any radiation that offers high resolving power damages the objects it strikes. According to calculations made by David Sayre and his colleagues, under optimal microscopy conditions soft X rays will do slightly less damage than electrons. This advantage comes into play, however, only if all the radiation that penetrated and damaged the specimen is exploited to analyze it. That is not the case with contact X-ray microscopy. The resist absorbs only a small fraction (less than 1 percent for the highest resolution) of the incident X-ray photons. The majority of the photons that pass through the specimen do not contribute to the image. If a scanning X-ray microscope could be built with a focusing element, it would be able to produce an image of the same quality with only about a hundredth of the radiation damage.

In such X-ray microscopes of the future the recording medium could be not photographic film or an X-ray resist but a photon counter. Equipped with a digital memory, the photon counter would record the transmitted intensity of an X-ray beam that had scanned the specimen and would project an image of the specimen's absorption features on a television screen. The digital storage of the image would facilitate further analysis. For example, microscopists could obtain an image of the distribution of an element such as calcium in an object by having the television screen subtract only two images, one made with a wavelength just above the absorption edge of the element and the other made with a wavelength just below it. To perform the same subtraction with two resist images would be extremely laborious. In 1972 a first version of such a scanning X-ray microscope was built by Paul Horowitz and John A. Howell of Harvard University based on a pinhole illuminated by synchrotron radiation to define the exposed area of the specimen. The diameter of the pinhole limited the resolution to about one micrometer, which would be greatly improved by better focusing devices.

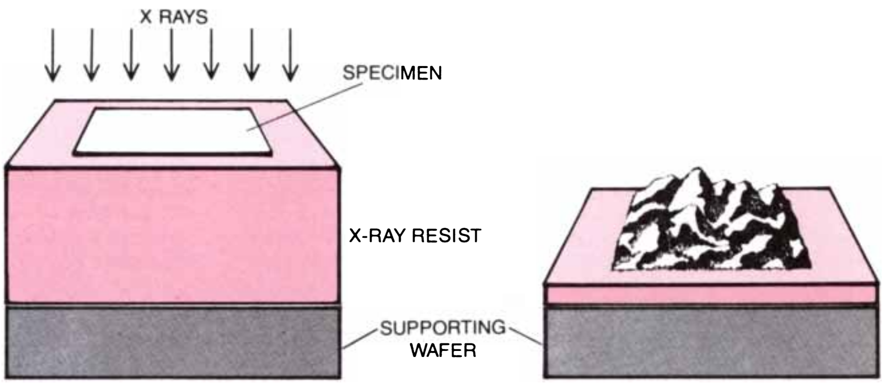
In search of high-quality focusing elements physicists have concentrated on grazing-incidence mirrors. They have also recently begun to work with zone plates and normal-incidence mirrors. To explain how these devices function calls for a brief discussion of the wave mechanics of image formation. When two or more waves cross one another they interfere, or combine, to form a wave field whose amplitude at any given point equals the sum of the amplitudes of the component waves [*see illustrations on next page*]. Where the waves are exactly in phase (crests coinciding and troughs coinciding), the amplitude is increased, and where they are exactly out of phase (crests coinciding with troughs) the amplitude is decreased.

When the waves combine to form a standing wave, an interference pattern is created, which is characterized by points of maximum intensity designated antinodes and points of minimum intensity designated nodes. The nodes will have zero intensity if the interfering waves have the same amplitude. The term standing wave refers to the fact that the antinodes and nodes remain stationary, even though the component waves that generated the standing wave are traveling at the speed of light. Since the antinodes are the points of maximum intensity and the nodes are the points of minimum intensity, a photograph of the interference pattern will appear brightest at the antinodes and darkest at the nodes.

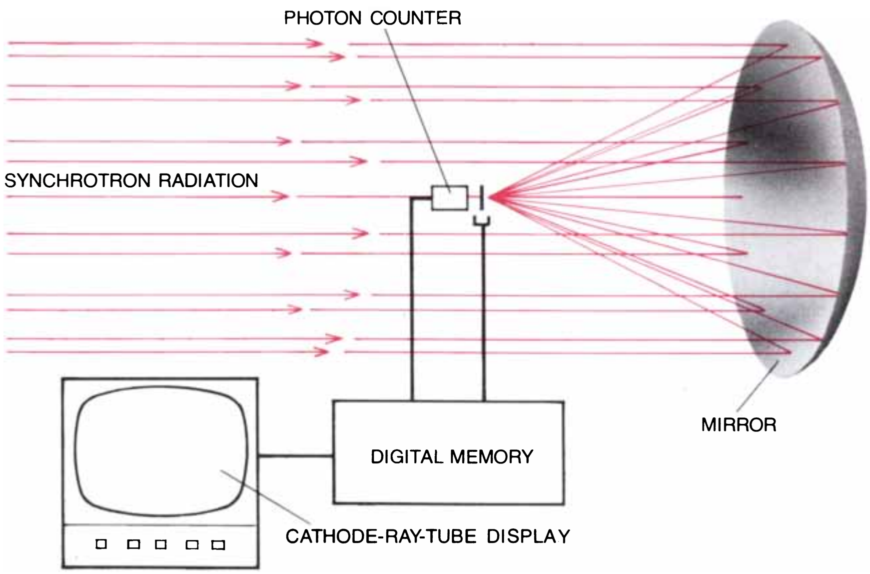
In many optical applications it is the ability of interference patterns to reconstruct the interfering waves that is exploited. If a grating made in the form of an interference pattern of two waves is illuminated with one of the waves, the other wave will be generated. This reconstruction phenomenon, which is the basis of holography, is the basis for one recent effort to focus X rays. The grating called a Fresnel zone plate is made from the interference pattern between a plane wave and a spherical wave [*see bottom illustration on page 77 and top illustration on page 78*]. When the zone plate is illuminated with an X-ray plane wave, a converging spherical wave will come out. In this way the zone plate



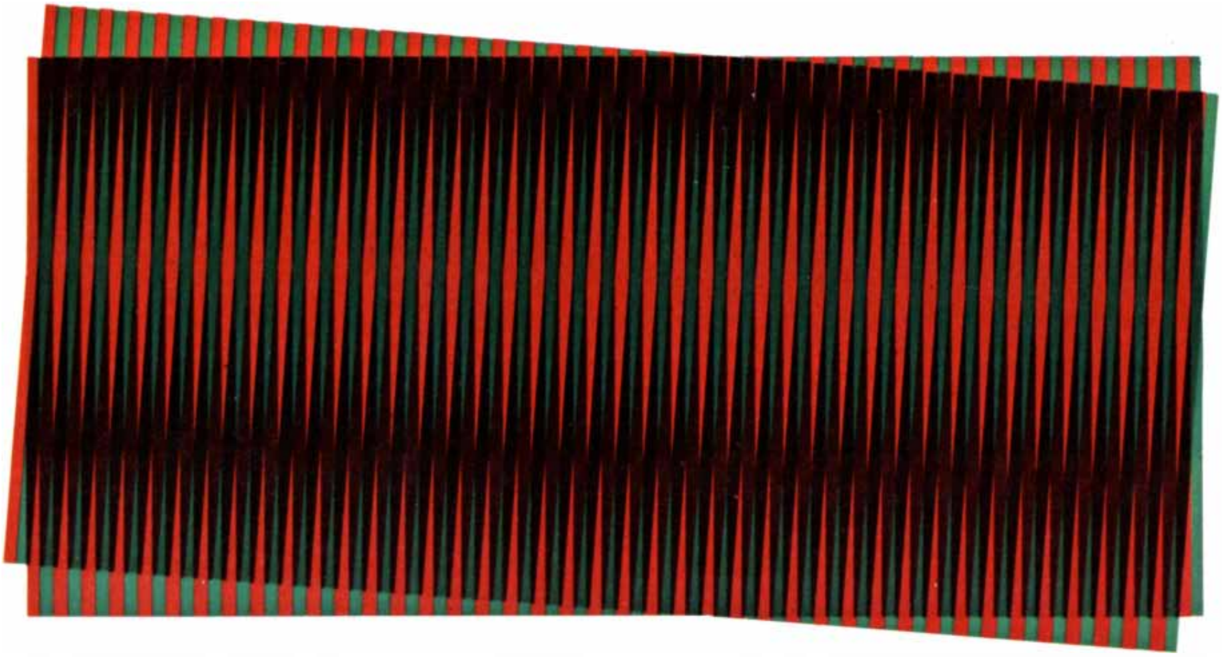
GLASS LENSES can focus light waves but not X rays. Here a spherical light wave that diverges from a point is changed by a lens into a spherical wave that converges to a point. The lens delays wave fronts passing through its center more than wave fronts passing through its edges in such a way that the time it takes for light to travel from object to image is the same for all paths.



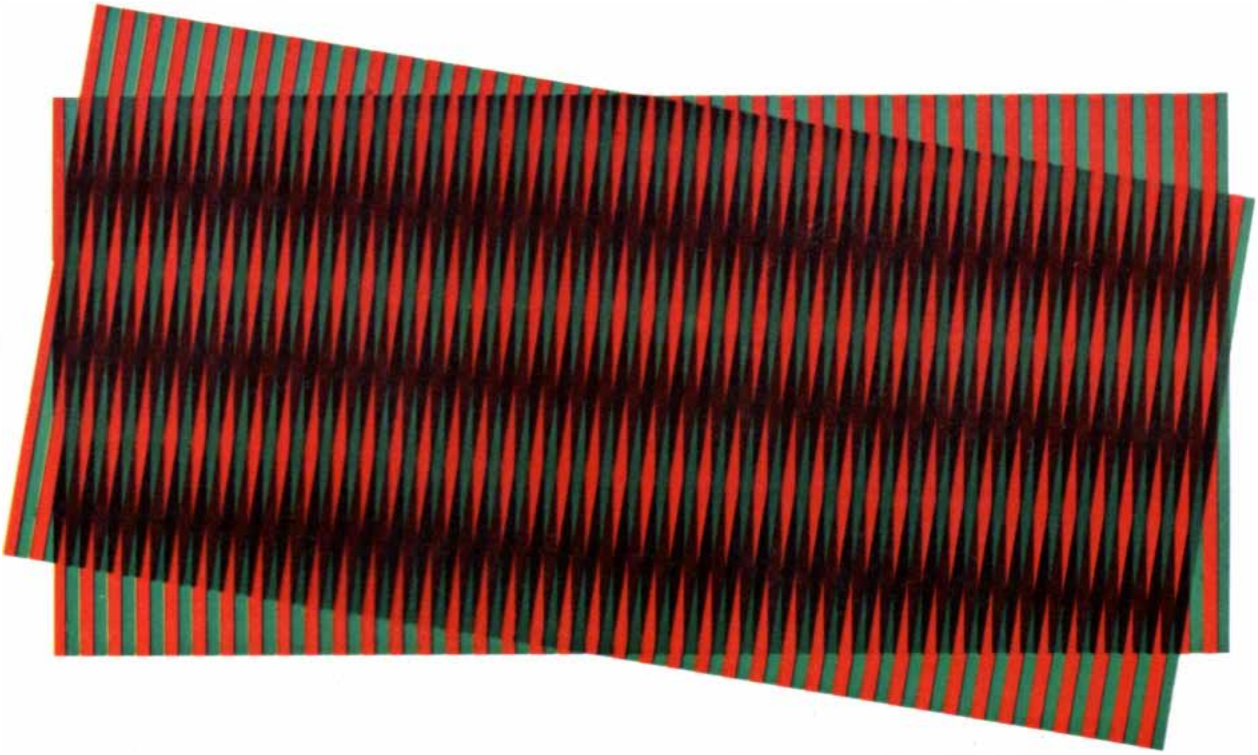
X-RAY RESIST is the polymer used for microelectronic-circuit lithography and replica microscopy. In microscopy the solubility of a layer of resist placed behind a specimen (*left*) will vary from point to point according to the amount of radiation the layer receives. When the layer is washed in a solvent, it will selectively dissolve to form a relief image of the specimen, with the highest relief areas corresponding to the regions of highest absorption in the specimen (*right*).



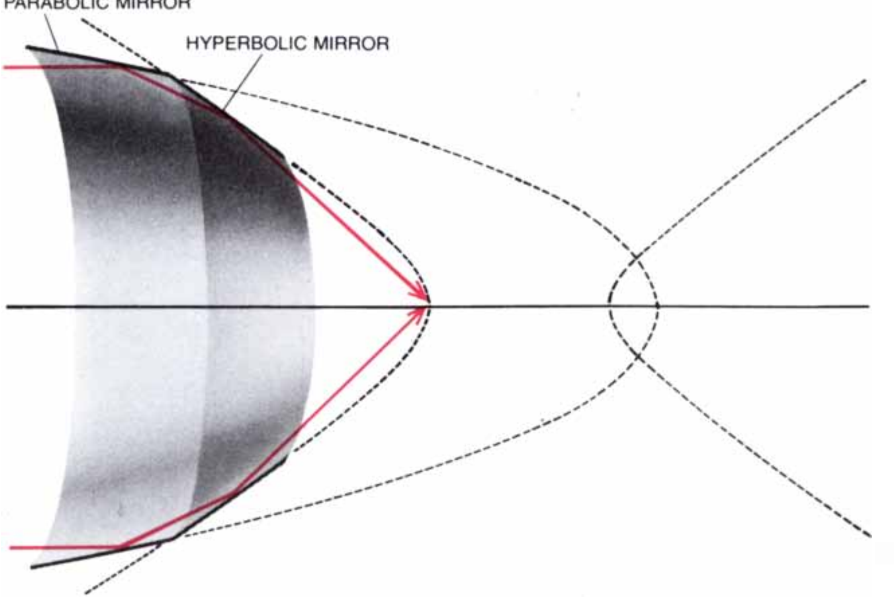
X-RAY MICROSCOPES of the future might have a photon counter as the recording medium instead of an X-ray resist. If the microscope were equipped with a focusing element such as a mirror, it could produce an image of the same quality as contact X-ray microscopy can but with only about a hundredth of the radiation dose. Less radiation would mean less damage to the specimen. A digital memory would record the intensity of the X rays that had passed through, and a television screen would display an image of the specimen's absorption features. The digital storage of the image would then facilitate quantitative analysis of the spectrum.



TWO PLANE WAVES of equal amplitude, each represented as an alternating series of red and green lines with red corresponding to troughs and green to crests, can combine to form an interference pattern, which is characterized by points of maximum intensity called antinodes and points at rest called nodes. The nodes are dark areas where crests of one of the plane waves exactly cancel troughs of the other. The antinodes are both intense red areas where troughs coincide and intense green areas where crests coincide. The interference pattern is a standing wave since nodes and antinodes remain in the same place even when the plane waves move at the speed of light.



DISTANCE BETWEEN NODES and distance between antinodes decrease when the angle between the traveling plane waves is increased. The surface of a mirror corresponds to a node in the interference pattern between an incident plane wave and a reflected one.



X-RAY TELESCOPE aboard the Skylab satellites is of the Wolter type, in which radiation that comes in at a grazing angle of .916 degree is reflected by hyperbolic and parabolic surfaces toward an image point. Here the angle of incidence is exaggerated and the reflecting surfaces are extended by broken lines to show the conic sections of which the surfaces are part. The telescope can focus X rays whose wavelengths are greater than six angstroms with a resolution of about one second of arc, a value that is 1,000 times worse than the theoretical limit.

brings X rays together to a focal point.

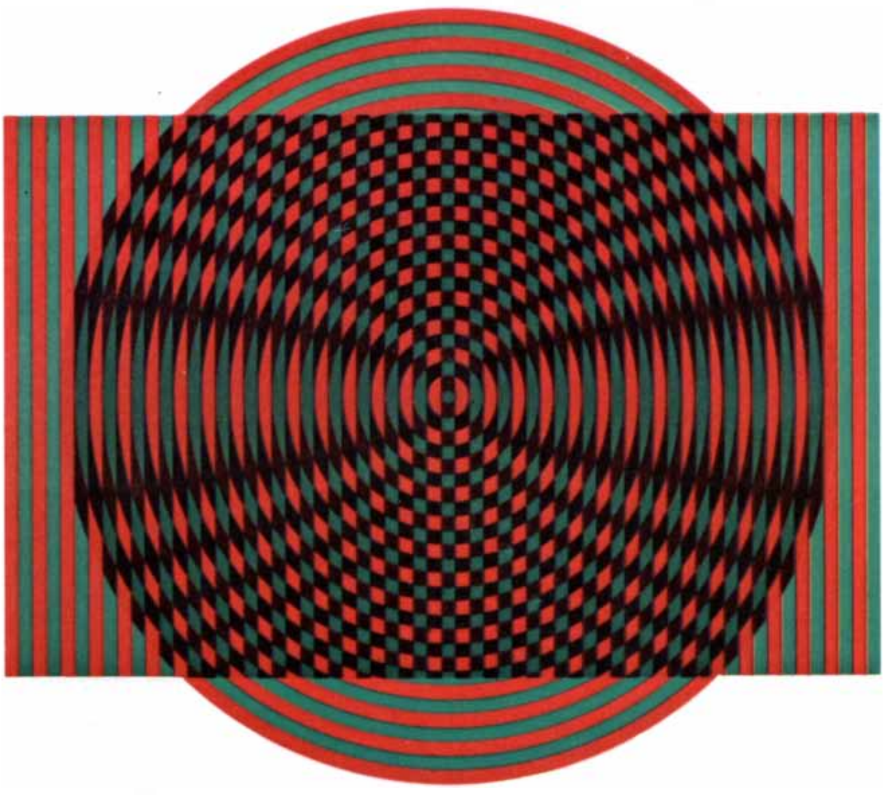
The zone plate, which is a series of concentric circles that get thinner and closer together as their radii increase, can achieve a resolution that is equal to the width of the smallest zone, or narrowest space, between the circles. Attaining this resolution, however, requires that the zone plate be fabricated by a process of comparable resolution. Electron-beam systems can furnish suitable resolving power, and for the past 10 years a group of physicists at the University of Tübingen has constructed zone plates with them. Although plates with zones of less than 300 angstroms have been made, none has yet provided a usable resolution better than that of the light microscope. The best resolution of an X-ray microscope equipped with a zone plate for a focusing mechanism is about .5 micrometer, five times the theoretical limit of .1 micrometer; it was achieved in an instrument built at the University of Göttingen by E. Niemann, D. Rudolph and G. Schmahl. As the techniques for fabricating zone plates are improved over the next few years, the resolution will undoubtedly come closer to the theoretical limit.

The main disadvantage of the zone plate as an imaging device is that it calls for monochromatic radiation. The focal length of a zone plate is inversely proportional to the wavelength of the incident radiation, and so only one wavelength in a beam of polychromatic radiation will form a sharp image. This means that zone plates cannot take advantage of the wide spectrum of the X rays generated by synchrotrons. If intense sources of monochromatic soft X rays are ever developed, however, zone plates will make effective imagers.

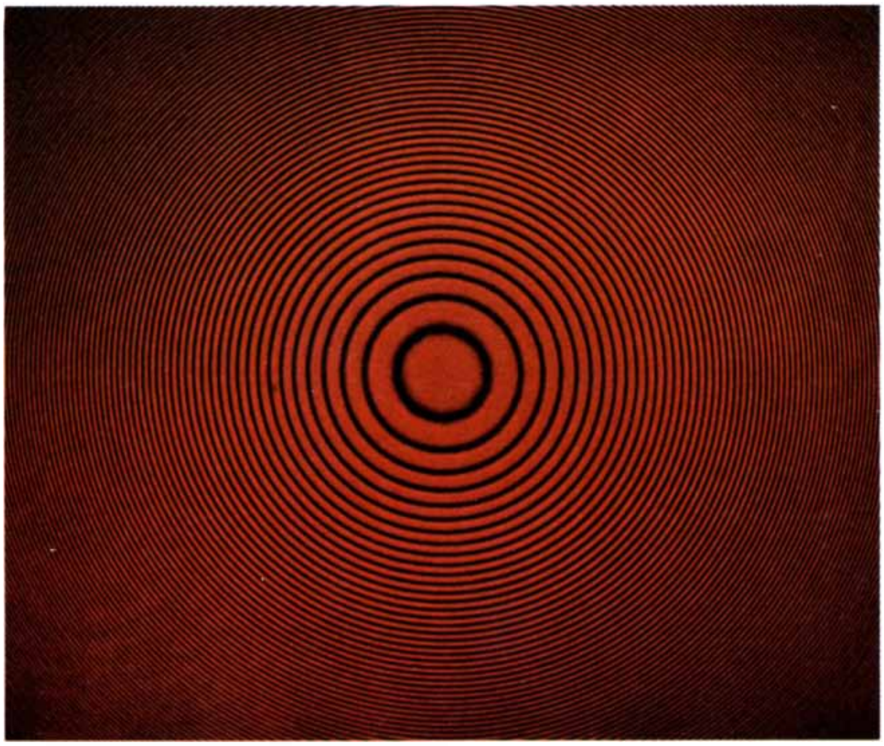
Unlike zone plates, mirrors can focus different wavelengths simultaneously. From the viewpoint of wave mechanics the surface of a perfect mirror can be described as a surface that coincides with one node of an interference pattern created by the waves incident on the mirror and those reflected from it. In other words, if a mirror has 100 percent reflectivity, which means that the incident and reflected waves have the same amplitude, it corresponds to a region of zero intensity. If the mirror does not force a node with zero intensity on the incident wave, it will reflect a wave whose intensity is less than that of the incident wave. The surface of the mirror must completely attenuate the incident wave within a fraction of a wavelength if it is to create a node with zero intensity. Incomplete attenuation would generate a node with nonzero intensity, corresponding to incident and reflected waves of unequal amplitude, or to low reflectivity.

For all materials, however, the absorption of soft X rays is much too low to achieve the desired attenuation. Waves that are 50 angstroms long, for example, will travel at least 500 angstroms into any material. At that wavelength and at angles of incidence close to the perpendicular, mirrors reflect only a hundred-thousandth of the incident radiation.

A mirror ordinarily has a single smooth surface. Our own work on X-ray mirrors at the Thomas J. Watson Research Center of the International Business Machines Corporation has concentrated on achieving better reflectivity with mirrors that have many surfaces on top of one another. When two



PARABOLIC CONFIGURATION OF NODES characterizes the interference pattern between a spherical wave and a plane one. A cross section of the pattern is the series of concentric circles called a zone plate, which appears in the photograph at the top of the next page.



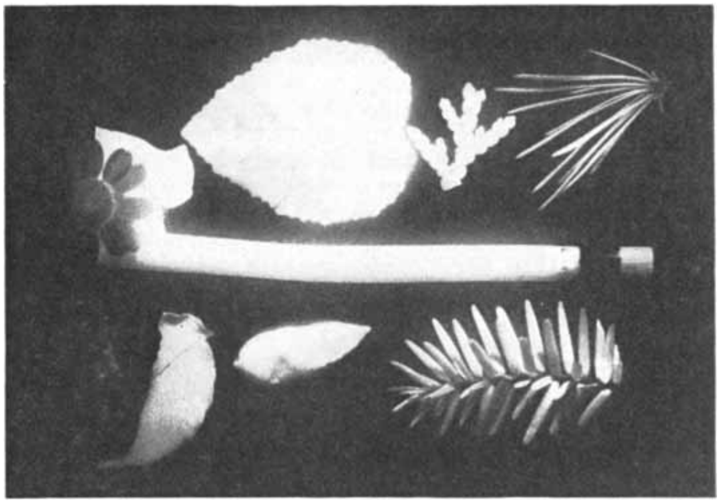
FRESNEL ZONE PLATE, a series of concentric circles that get thinner and closer together as their radii increase, is a cross section of the interference pattern that can be seen at the bottom of the preceding page. When a plane wave of X rays strikes the Fresnel zone plate, it is diffracted as a spherical wave that converges to an image point. The Fresnel zone plate provides a resolution equal to the width of the narrowest zone, or spacing, between the concentric circles.

SUN'S CORONA emits X rays, which are color-coded in this photograph made with the Skylab X-ray telescope depicted at the top of the preceding page. The colors progress from red (faint emission) to white (intense emission). The rainbow-hued regions enclose areas that emit the most X-radiation and indicate that there is activity at lower levels in the sun's atmosphere. The large coronal hole is a region of decreased density, temperature and X-ray emission that is surrounded by "open" magnetic fields and is associated with fast streams in the solar "wind."

plane waves such as an incident and a reflected wave cross each other, a large number of nodes will appear in the interference pattern. By positioning an absorbing material so that it occupies a large number of nodes in the interference pattern one could obtain a higher reflectivity than one could with a mirror consisting of a single smooth surface. Although it had been known for a long time that natural crystals will strongly reflect short X rays if the atoms in the crystal are located at the nodes, it has been realized only recently that artificial materials can be fabricated that will strongly reflect soft X rays at angles of incidence close to the perpendicular. The production of soft-X-ray mirrors can be described as the fabrication of artificial materials in which highly absorbing regions alternate with weakly absorbing ones in such a way that the positions of the two regions match the desired interference pattern. With such materials we expect to observe reflectivities of up to 30 percent. In collaboration with R.-P. Haelbich and C. Kunz at the German Electron Synchrotron Laboratory (DESY) in Hamburg we are trying to make multilayer mirrors for the wavelength region between 50 and 200 angstroms. Our long-term goal is to construct a scanning X-ray microscope incorporating such mirrors to focus the radiation.

Although an ordinary mirror will reflect scarcely at all soft X rays that impinge on it at angles close to the perpendicular, it will adequately reflect those waves that just graze its surface at a very low angle. At such a grazing incidence the nodes of the interference pattern between the incident and the reflected waves are spaced farther apart. The coarser interference pattern makes it possible to position more absorbing material at the node of the standing wave. For this reason greater reflectivities can be obtained with all materials at grazing incidence. Moreover, at very low grazing angles the reflectivity is increased by another effect: total reflection. Mirrors of this kind have served to focus soft X rays in such instruments as the X-ray telescope aboard the Skylab satellites [*see top illustration on preceding page*]. That telescope, operating at a grazing angle of .916 degree, was able to focus soft X rays whose wavelengths were greater than six angstroms. Its resolution was limited, however, by the unavoidably imperfect reflecting surfaces to about one second of arc, a value 1,000 times worse than the theoretical limit. This again illustrates a major problem with all high-quality focusing elements for X rays: the elements have to be fabricated with high precision. Recent progress in fabrication techniques, however, promises substantial advances over the next few years.

Photography by infrared



Biological substances fluorescing in infrared from excitation by visible light.

To make such pictures one illuminates through blue-green filters that pass very little infrared and photographs through filters that pass infrared and as little else as possible. There are minerals and organic substances besides chlorophyll that can be thus simply picked from a background by their infrared fluorescence.

We get more inquiries, though, about picturing warm objects by their emitted radiation. If the objects are no warmer than 250°C, you are not likely to bring it off with just a camera, film, and filters. Kodak Publication P-570 ("Thermal Photography"), available on request from Dept. 55W, Kodak, Rochester, N.Y. 14650, goes into detail on that.

> "There is no fundamental difference between the practice of infrared photography and that in which the visible region of the spectrum (light) is used. Anyone equipped for photography with ordinary films can make infrared photographs on infrared films without investing in any extra equipment other than a camera lens filter and sometimes filters over the lights."

Encouraging statement with which H. Lou Gibson, who pioneered the above techniques, opens the second chapter in his new edition of *Photography By Infrared* (John Wiley & Son, 1978). Other chapters in the book:

- On Infrared: Its History, Nature, and Applications
- Basic Physics of Infrared Recording
- Documents, Artifacts, Art, Textiles, Graphic Arts
- Medical Infrared Photography
- Investigations in the Natural Sciences
- Infrared Photomicrography
- Technical Applications
- Remote Sensing, Aerial and Orbital
- Herschel Effect and Indirect Recording

Mr. Gibson at about the time he joined Kodak and Mr. Gibson in 1978, some years after retirement from Kodak.

People of Gibson's and Clark's generation know that the size of the capital equipment budget is not the only valid measure of a laboratory's competence.

Dr. Walter Clark, the book's editor, as a member of the Kodak Research Laboratories management at about the time he wrote the first two editions of *Photography By Infrared.* Dr. Clark in 1978, some years after retirement from Kodak.

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KODAK High Speed Infrared Film 4143 (ESTAR Thick Base), 4 x 5 inches
KODAK EKTACHROME Infrared Film in 35 mm, 20-exp magazines (for "false color")
KODAK Infrared AEROGRAPHIC Film 2424 (ESTAR Base) in 70 mm and other aerial film sizes
KODAK AEROCHROME Infrared Film 2443 (ESTAR Base) in 70 mm and other aerial film sizes (for "false color")
KODAK "Spectroscopic" Plates and Films, Types I-N, IV-N, and I-Z
KODAK WRATTEN Filters, Nos. 87, 87A, 87B, 87C, 88A, and 89B
Kodak Publication M-28, "Applied Infrared Photography"
Kodak Publication M-29, "Kodak Data for Aerial Photography"
Kodak Publication N-17, "KODAK Infrared Films"
Kodak Publication P-315, "KODAK Plates and Films for Scientific Photography"

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The Case of the CT Scanner

The introduction of new technology is one of the main elements fueling the continuous rise in the cost of health care, which increased its claim on U.S. resources from 5.2 percent of the gross national product in the fiscal year 1960 to 8.2 percent in 1975 and 8.8 percent in 1977. Every new therapeutic or diagnostic tool added to the armamentarium of physicians and hospitals represents an additional cost; if it is expensive to acquire and operate, if it does not completely replace established procedures and if it is enthusiastically received, widely adopted and frequently prescribed, the inflationary effect is enhanced.

No new medical tool is more illustrative of such technological inflation than the computed tomography (CT) scanner, which combines X-ray apparatus with a computer and a cathode-ray tube to produce images of cross sections of the head or body. The CT scanner was developed in Britain in the late 1960's and was introduced into the U.S. in 1973; by the end of 1977 almost 1,000 scanners were being operated in this country. The proliferation of the devices, the frequency of their use and the high expenditures associated with them have combined to provide a case study of the relation between expensive technology and medical costs, stimulating an ongoing debate about how to control the installation and utilization of new devices so as to balance economic and medical considerations in providing effective, affordable health care. A recent study by the Congressional Office of Technology Assessment (OTA) examines the CT scanner as illustrative of these issues. The OTA reports a large number of findings, identifies the policy problems that are raised and rather than making specific recommendations suggests some policy alternatives.

The scanners proliferated in the U.S., according to the report, without the benefit of broad, carefully designed studies assessing their efficacy compared with existing procedures, although there are many clinical reports indicating that CT head and body scanning is reliable and accurate. The new procedure has replaced other diagnostic methods to some extent, but it has produced "a considerable net increase" in total procedures performed. It seems to be relatively safe; the risk from CT head scanning in particular appears to be lower than that from older procedures and the pain and discomfort "are definitely lower in many cases."

Of the scanners known to be operating in the U.S. in mid-1977 (nearly three-fifths of them head scanners and the remainder body scanners) 81 percent were in hospitals (mostly large, nonprofit community hospitals) and the rest were in private offices and clinics; some of those installed in hospitals were actually owned or leased by physicians. (Private purchase is encouraged by the fact that it circumvents certain regulatory procedures.) The rate of installation increased steadily through 1976 but may have slowed down since then. The commonest diagnoses on the basis of head scans have been tumors, cerebrovascular occlusion or hemorrhage, and diseases that enlarge the ventricular spaces of the brain. The procedure is also valuable for patients with head trauma; it is sometimes ordered for headache, and there has been some tendency to resort to scanning for screening purposes. In 1977 most CT scans were done by radiologists at the request of a referring physician; "self-referral" (by the physician who proceeds to do the scan and is paid for it) was the case for only about a tenth of the devices.

The average price of a CT scanner was close to $500,000 for the first few years after their introduction, but recently several companies have marketed new versions of the head scanner for about $100,000. The scanner is typically depreciated over a five-year period (compared with eight years for most equipment), adding to the annual expense of operation, estimates of which ranged from $259,000 to $379,000 for 1975 and 1976. The average fee for a CT head examination ranged from $240 to $260. The estimated annual "profit" per CT scanner (revenue minus expenses) in 1976 ranged from $51,000 to $291,000, or from 11 to 65 percent of the purchase price of a $450,000 device.

The major policy problems associated with the CT scanner derive from the lack of control over the acquisition and the utilization of the devices. A hospital seeking to install a scanner must have a certificate of need from a state health planning and development agency. Inadequate guidelines have been available for such approval, and the guidelines vary in different states. The exemption of private physicians from certificate-of-need provisions, and the potential profits from scanning, encourage the acquisition of scanners by physicians. Once a scanner is acquired (by a hospital or a physician) its use in a particular case is not subject to review. "By its reimbursement methods, the Federal Government in effect has assumed an open-ended commitment to finance services."

Two of the OTA's seven policy alternatives (which are not mutually exclusive) deal with developing information on safety and efficacy. One alternative would be to establish a formal process for identifying medical technologies that require assessment of safety and efficacy, to conduct the evaluations and then synthesize and disseminate the results. A second alternative would be to go on to make official judgments about efficacy and safety, in effect providing a formal (although not mandatory) set of indications for appropriate applications of a technology.

Three alternatives suggest possible changes in regulatory policies. Under alternative No. 3 a Federal agency such as the Food and Drug Administration would be authorized to actually restrict use of a device to conditions specified by the FDA. (The report suggests that such restriction might not be practical or advisable.) Alternative No. 4 would link Medicare reimbursement to the information and judgments resulting from alternatives Nos. 1 and 2. Alternative No. 5 would expand the regulation of capital expenditures to cover equipment regardless of ownership or location.

The last group of alternatives would affect the financing of medical care more broadly. Alternative No. 6 would establish Medicare and Medicaid rates of payment based on efficiency, thereby tending to control the initial cost, the degree of utilization and the profit-taking associated with a technology. Alternative No. 7 would fundamentally restructure the payment system to encourage efficiency, primarily by fixing the total revenue of a health-care provider in advance of delivery, as by a system of capitation payments or by reviewing the provider's budget.

Upsilon Updated

The upsilon particle, which has a mass more than three times greater than any other subatomic entity yet detected, was discovered last year in energetic collisions between protons and copper nuclei (see "The Upsilon Particle," by Leon M. Lederman; SCIENTIFIC AMERICAN, October). With a mass in its lowest energy state equivalent to 9.0 GeV (billion electron volts) and masses in excited states equivalent to 10.0 and 10.4 GeV, the upsilon particle has been interpreted as consisting of a massive new quark (the fifth) bound to its antiquark. The existence of the upsilon particle's lowest excited state has now been confirmed for the first time by a group of investigators at the DESY (Deutsches Elektronen Synchrotron) laboratory in Hamburg. The investigators are the same ones who had confirmed the exis-

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tence of the upsilon particle in its lowest energy state.

At DESY the excited upsilon particle showed up as a resonance, or peak, in the yield of hadrons (particles that are subject to the nuclear, or "strong," force) that emerged from electron-positron collisions in a storage-ring accelerator. The DESY storage ring had many advantages over the 400-GeV synchrotron at the Fermi National Accelerator Laboratory (Fermilab), which was used by Leon M. Lederman of Columbia University and his collaborators to discover the upsilon particle. At Fermilab the excited upsilon particle appeared as a resonance in the yield of muons generated in collisions between protons and nuclei. (The muon is a lepton, a particle that is not subject to the nuclear force, that has 200 times the mass of the electron but otherwise exhibits the same properties.) In the DESY storage ring beams of electrons and positrons, or antielectrons, moved in opposite directions around a circular track. Where the beams crossed, electrons and positrons collided and annihilated each other. The particles collided only once or twice a second, and so it was much easier to study the interactions than it was at Fermilab, where there were 10^{11} proton-nucleus interactions per second. As a result the DESY investigators have recently measured the mass of the excited upsilon particle with an accuracy 20 times better than that achieved at Fermilab.

The DESY experiment confirmed the fact that the excited upsilon particle has a long lifetime for a subatomic particle, as Lederman and his collaborators had originally suggested. A long lifetime means that the upsilon particle is inhibited from decaying into such particles as pions, kaons and protons, all of which are made up of four kinds of quark. Since one kind of quark cannot easily change into another kind, the interpretation of the upsilon particle as being composed of a fifth quark explains why the upsilon particle does not readily decay into particles made up of the four other quarks.

The recent work at DESY also confirms the important prediction of the quark hypothesis that two "jets" of particles would emerge from electron-positron annihilations. The hypothesis suggests that either a pair of leptons or a pair of quarks would form whenever an electron and a positron annihilated each other. The quarks in such a pair would recoil rapidly and lose energy by creating other quarks that would bind together to form particles. The momentum of each of these particles would lie mainly in the direction of the momentum of one of the quarks in the original pair. This means that the particles should manifest themselves as two jets, or cones, aimed outward from the annihilation point. The quark hypothesis predicted that at the high energies available at DESY the jets would be very narrow. Indeed they are; what was seen in the experiment fully matches the theoretical prediction.

Salt Rivers of the Andes

In a broad bend of the Huallaga River in eastern Peru an exploring geochemist came on a spectacular sight. Stretching eight kilometers along the river and 100 meters into the air was a glistening white cliff of salt. The river, one of the major tributaries of the Amazon, is eating into a huge deposit of rock salt. John M. Edmond of the Massachusetts Institute of Technology reports that the salt cliff is only one indication of the abundance of exposed salt deposits in the region of the Amazon headwaters in the Andes of eastern Peru and Ecuador. Edmond, who is working to develop a geochemical model of the Amazon, found that the salt deposits play an important part in determining the chemical composition of the river.

The compression forces associated with the building of the Andes, Edmond explains, were responsible for the many exposed deposits of rock salt in the region. Under pressure rock salt flows like glacial ice, and so the tremendous stresses of geological uplift squeezed salt from deep deposits up through cracks and faults in the overlying rock. In this way large salt domes were formed on the surface. In some areas there are even pinnacles of salt reaching a height of several meters.

Edmond discovered that large quantities of salt from the deposits are dissolved by rainfall and washed into the Amazon headwater system. As a result many of the streams and rivers are so salty that neither human beings nor animals drink from them. Although the salinity of the salty streams and rivers that feed into the Amazon is diluted downstream, it is still a major controlling factor in the overall chemistry of the river. Edmond reports that analysis of water samples collected in the Peruvian Andes indicates that the dissolved salt in the salty tributaries accounts for at least half of the sodium and chlorine in the Amazon.

Hans, Sherman and Austin

Ever since "Clever Hans," a famous calculating horse, amazed Berliners early in the century, careful experimenters in animal psychology have been wary of what is sometimes called the Clever Hans effect. All Hans's feats, it was finally discovered, had been simple "go, no go" responses to cues unconsciously given the horse by its handler-owner. Eliminating the Clever Hans effect from animal experiments is always troublesome, and it has been particularly so in efforts to determine whether nonhuman primates are capable of symbolic communication. Chimpanzees, the animals most often chosen for such research, must undergo training that involves a high level of social interaction between the animal subject and the human experimenter. Now an ingenious experiment conducted at the Yerkes Regional Primate Research Center at Emory University has demonstrated a capacity for symbolic communication between two chimpanzees in the absence of any possible cueing.

Writing in *Science,* E. Sue Savage-Rumbaugh of the Yerkes center and her colleagues give the results of a series of food-request tests involving interaction between a $4\frac{1}{2}$-year-old chimpanzee, Sherman, and a $3\frac{1}{2}$-year-old, Austin. Both animals had been born at the Yerkes center and were trained to recognize more than 30 geometric symbols, each one representing a word in English. Both had also learned to manipulate a keyboard bearing the symbols; when the chimpanzee depressed a key, the same symbol that was on the key appeared on a screen visible to the animal. Additional training, preliminary to the food-request tests, taught both animals 11 symbols equivalent to 11 kinds of food and drink. This added vocabulary training required 102 trials for Sherman and 201 trials for Austin.

In the tests the two animals alternated in the role of "informer" and "observer." In each trial the informer was taken to a room adjacent to the keyboard room; there it watched food being sealed in an opaque box. The informer and the sealed box were then taken to the keyboard room, where the observer was waiting. Using a keyboard in a separate room to avoid the possibility of cueing, one of the experimenters put on the keyboard-room screen symbols for the words "What this?" The informer then used its own keyboard to reply by putting the appropriate food symbol on the screen. The observer was thereupon given access to the keyboard and allowed to "request" the designated food. If either the observer or the informer responded with the wrong symbol, it was allowed to inspect the opened box to show that it had made a mistake but was not allowed to eat or drink the contents of the box. If both animals replied correctly, however, they were rewarded with the contents.

In a total of 158 trials, involving four different means of information exchange between the informer and the observer, Sherman and Austin alternately identified and requested the correct food in more than 90 percent of the trials. In one of the four variations of the experiment, after the observer had requested the food identified by the informer, the animal was presented with three photographs of food; two of the photographs had been selected at ran-

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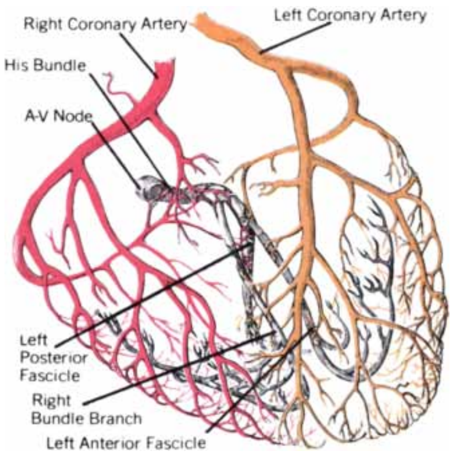

Branches of the right and left coronary arteries supply blood to the AV node and intraventricular conduction system.

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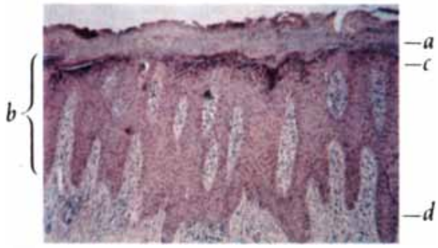

Histopathologic changes in psoriasis.

Extensive psoriasis (top) cleared completely (bottom) after four weeks of treatment with anthralin.

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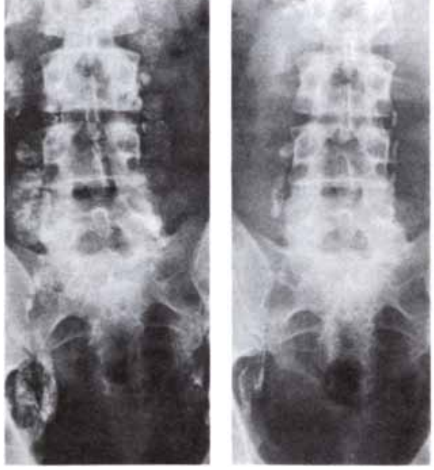

Extensive retroperitoneal Hodgkin's disease before and after MOPP chemotherapy.

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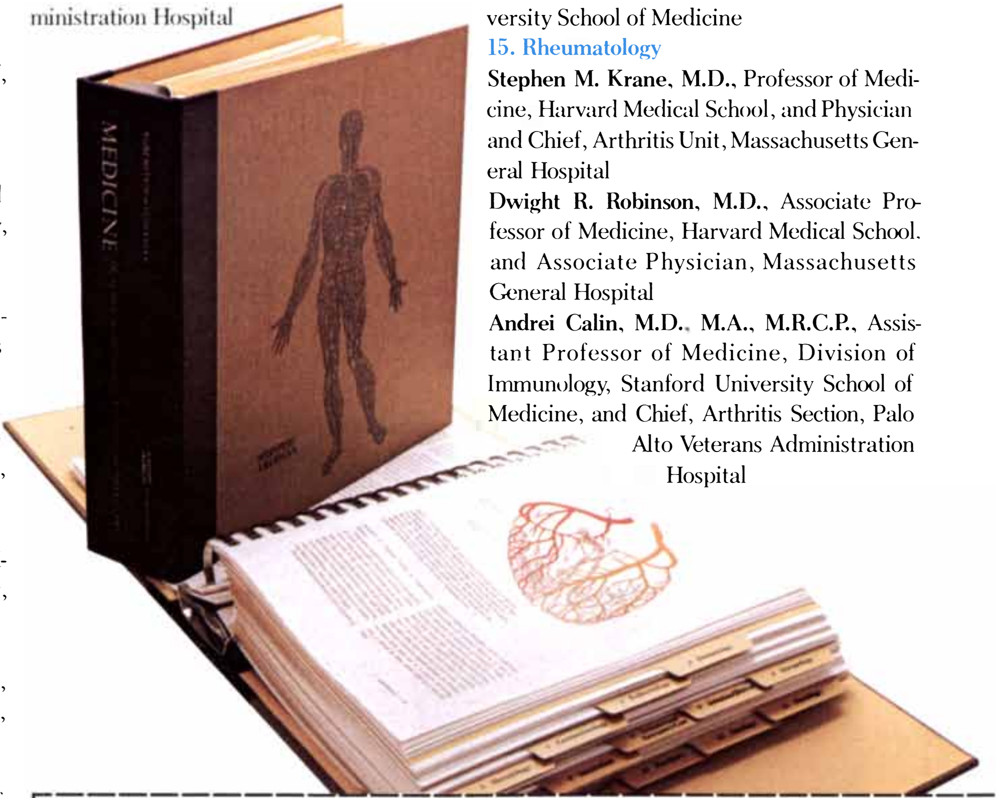

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City______________ State__________ Zip__________ dom and the third showed the food that was sealed in the box. On presentation the observer was required to select the appropriate photograph. The informer and the observer were rewarded only if both the symbolic and the photographic identifications were correct. This variation was designed to discover whether the observer was simply "matching," that is, punching whatever symbol key matched the symbol punched by the informer. The score in this test too was 90 percent accurate (27 of 30 trials were correct).

Throughout the four main tests the experimenter who supervised the animals in the keyboard room was himself not aware of the contents of the food boxes, a condition that prevented any cueing of the subjects, involuntary or otherwise. To assess the further possibility that the animal acting as the informer might be cueing the animal acting as the observer in some way other than by selecting a symbol, a fifth test was conducted. On returning to the keyboard room the informer was not allowed access to the keyboard and so could not put the appropriate symbol on the screen. In 26 trials under these conditions the observer finally keyed a food symbol; the animal was right, however, only four times, an error rate of 80 percent. A score that low indicates that cueing in any way other than by putting a symbol on the screen was an insignificant factor in communication between the two chimpanzees. With the Clever Hans effect properly guarded against, Savage-Rumbaugh and her colleagues conclude that chimpanzees have a genuine innate potential for symbolic communication.

Close Encounters

The two spacecraft placed in orbit around Mars in the course of the U.S. Viking mission have continued to return an intermittent stream of information to the earth, not only about the planet itself but also about its two fascinating miniature moons, Phobos and Deimos. The latest closeup pictures of the Martian satellites to be processed and released, for example, contain a number of fresh clues to the nature of these misshapen, asteroid-size bodies. Although the new findings answer old questions about Phobos and Deimos, investigators of the moons report, they also raise "some unexpected puzzles."

The most striking revelation contained in the first high-resolution images of Phobos, recorded by the *Viking 1* orbiter in February, 1977, was that its surface is almost entirely covered by an array of long, more or less parallel grooves, typically 100 to 200 meters wide and 20 to 30 meters deep. Since then the Viking orbiters have been maneuvered back into the vicinity of the satellites on numerous occasions, pho-

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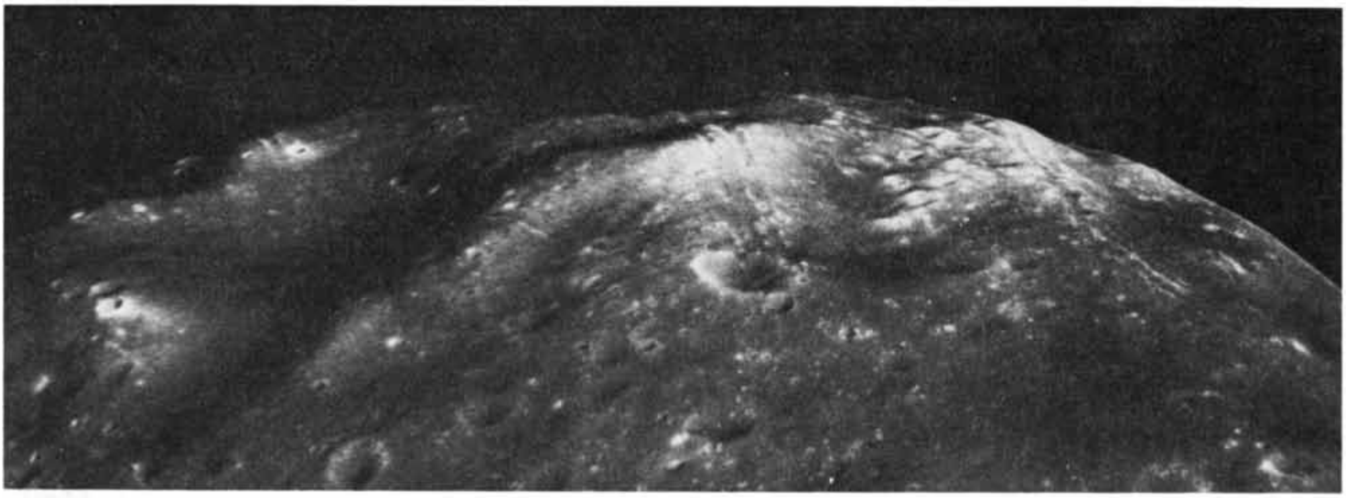
The improved coverage of Phobos has enabled Peter Thomas of Cornell University to map the distribution of grooves on virtually the entire surface of the satellite.

The new map of Phobos, published in a recent issue of *Sky and Telescope,* shows clearly that the grooves are associated with the moon's largest crater, named Stickney, which is some 10 kilometers in diameter. In an article accompanying the map Thomas and his colleagues, Joseph Veverka of Cornell and Thomas Duxbury of the Jet Propulsion Laboratory of the California Institute of Technology, point out that "the grooves are widest and best developed near Stickney and least prominent, in fact absent, on the other side of the satellite. This pattern strongly suggests that the grooves are connected with the formation of Stickney and may be surface by the severe impact that created the crater."

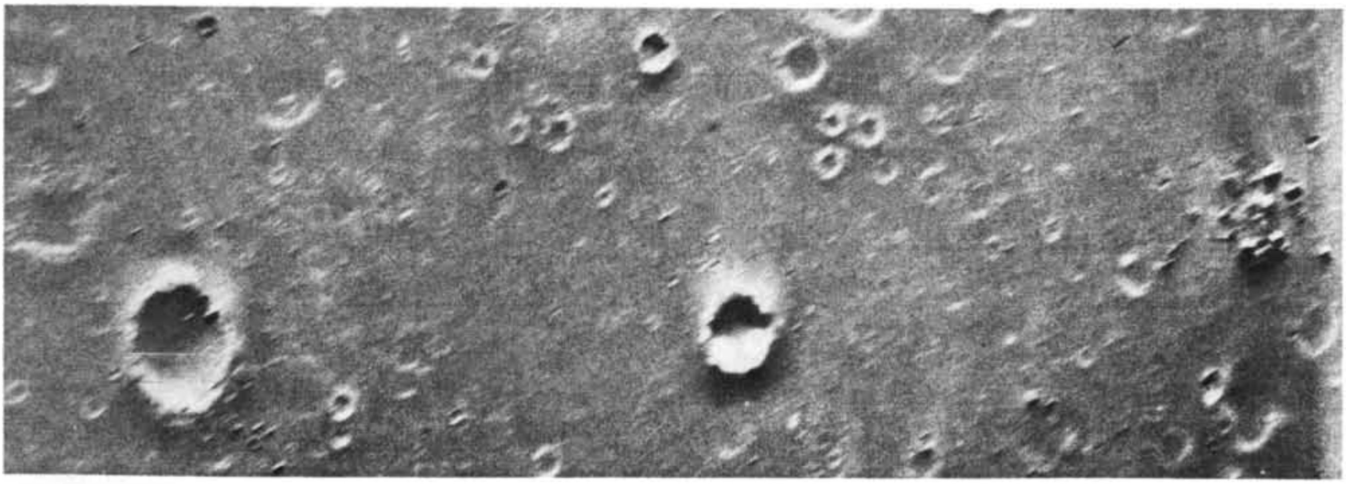
No such grooves appear on Deimos, possibly because there seem to be no craters on this body that are larger than about three kilometers in diameter. In fact, in all the Viking imagery, as in the earlier *Mariner 9* pictures, Deimos appears to be conspicuously smoother than Phobos. Yet when the craters are actually counted, about the same number are found on Deimos as on Phobos. According to the three authors of the *Sky and Telescope* article, "the very-high-resolution photographs obtained by the *Viking 2* orbiter during last October's flyby have finally resolved this apparent contradiction. These pictures, which resolve objects as small as two or three meters, revealed that Deimos is indeed heavily cratered. However, most of these craters—unlike on Phobos—are material that looks like crater ejecta. There are just as many craters on Deimos as on Phobos, but they tend to be masked by the fill."

The blanket of debris strewn over the surface of Deimos, ranging in size from fine grains to "clusters of house-sized blocks," raises an obvious question: Why do large amounts of such loose material litter Deimos but not Phobos? One possible explanation offered by the three investigators "is that the surfaces of the two satellites have significantly different mechanical properties. For example, an impact might produce a larger fraction of low-velocity fragments on Deimos than it would on Phobos."

Another factor might be that Phobos, the larger, inner satellite, "is so close to Mars that it might be easier to knock material off Phobos than off Deimos. With a density of only two grams per



ROUGH SURFACE OF PHOBOS, the larger of the two Martian satellites, is deeply pitted by numerous large craters, as can be seen in this picture made by the *Viking 1* orbiter in February, 1977, from a distance of some 440 kilometers. The scene is about 11 kilometers wide. The other main distinguishing feature of Phobos is the fact that it is scored by an array of long, narrow grooves, several of which can be seen in cross section near the limb. The grooves appear to be associated with the formation of Stickney, the moon's largest crater.



SMOOTH SURFACE OF DEIMOS turns out on close inspection to be just as heavily cratered as that of Phobos, as revealed in this *Viking 2* image, made in October, 1977, from a distance of only about 50 kilometers. The scene in this vertical overhead, extreme closeup view is approximately two kilometers wide. In earlier pictures made from farther away Deimos appeared to be conspicuously lacking in craters; the explanation for the comparatively unmarked appearance of Deimos is that its craters are partly filled with a blanket of loose debris, ranging in size from fine grains to house-size blocks (*right*). Deimos also seems to have no grooves or large craters on its surface.

cubic centimeter, Phobos is within the Roche limit of Mars. (A liquid satellite closer to Mars than this limit would be torn apart by tidal forces exerted by the planet.) Phobos remains intact because it is held together by cohesive forces as well as gravity. Whether this situation could account for the different surface appearance of Phobos remains to be worked out."

The evident differences between the two Martian satellites raise yet another question: Which of the two is more typical of other small objects in the solar system? The resolution of that "interesting issue," the authors suggest, calls for "future spacecraft exploration of small asteroids."

Missed Chance

When Ernst B. Chain and Howard W. Florey isolated penicillin in 1939, they traced the origin of their work to the observation of the antibacterial action of *Penicillium* mold by Alexander Fleming in 1928. It appears, however, that Fleming's discovery, like many others in science, had been anticipated. Moreover, it had been anticipated with remarkable explicitness. In 1896 the antibacterial action of *Penicillium* was unmistakably demonstrated by a 21-year-old French medical student named Ernest Augustin Clement Duchesne. Duchesne's pioneering work was ignored by his contemporaries, and his discovery was forgotten for 50 years. In a note in *The Journal of the American Medical Association* Robert A. Kyle and Marc A. Shampo of the Mayo Clinic suggest that Duchesne deserves full recognition for his remarkable work.

Duchesne was born in Paris on May 30, 1874. At 20 he entered the Army Medical Academy in Lyons. He had read the writings of Louis Pasteur and was engrossed in the study of microorganisms. He knew that if a single spore of mold fell onto a damp piece of bread, rotten fruit, cheese or jam, a thick growth of the mold would appear within a few days. In other places where molds might be expected to thrive, however, they were usually absent. For example, although mold cells were extremely prevalent in the air, they were hardly ever seen under the microscope in water that had been added to cultures of bacteria. Duchesne wondered whether the molds were killed by the bacteria. Encouraged by Gabriel Roux, director of the Institute of Public Hygiene, he began his thesis research on the question of the antagonism between bacteria and mold. As a test subject he chose the mold *Penicillium glaucum*.

Initially Duchesne found that the presence of bacteria in an environment in which mold was growing usually led to the rapid destruction of the mold. He asked himself, however, whether in the struggle for existence between molds and bacteria there might be certain conditions in which the mold would prevail. In one experiment he cultivated *Penicillium* on a piece of moist food and transferred *Escherichia coli* bacteria onto the mold. After a few hours he examined the mold and found that the bacteria had been killed.

His next step was to inoculate guinea pigs with virulent cultures of pathogenic microorganisms such as *E. coli* and typhoid bacteria. Then he injected half of the animals with nutrient broth on which *Penicillium* had been grown. The next day the animals that had received the injection of broth were alive and healthy but the animals that had not received it were dead. Apparently the growth of the bacteria in the animals had been inhibited by the crude extract of the mold represented by the broth.

A year after Duchesne had begun his experiments he described them in a 56-page dissertation titled (in translation from the French) "A Contribution to the Study of the Struggle for Existence of Microorganisms: Antagonism between Molds and Microbes." He observed that since he was a medical student, he had

had time to do only a few experiments and that in any case his work should be repeated and confirmed. "Further research," he added, "may lead to new developments that could prove directly applicable to prophylactic hygiene and therapy."

In 1897, at the age of 22, Duchesne received his M.D. degree. He became an army doctor, as had been his intention, and his assignment to a regiment in Senlis, north of Paris, made it impossible for him to continue his research. In 1902 he developed a lung disease (probably tuberculosis) and had to take a leave of absence. He returned to active duty the following year and served with a regiment in Clermont-Ferrand in south-central France. His illness became worse, however, and in 1907 he was obliged to end his army career. On August 30, 1912, at age 38, he died in Amélie-les-Bains, where he was being treated for his disease.

Duchesne's findings attracted no attention until his thesis was accidentally discovered by a librarian some 50 years after he had completed his experiments. As is the case with many other discoveries that were anticipated, it is not known why his work was ignored by the microbiologists of his time. There is no evidence that Roux, who had advised him on his research topic, or anyone else pursued his findings.

When Fleming, working at St. Mary's Hospital Medical School of the University of London, observed a bacteria-free circle around a green mold (*Penicillium notatum*) that had contaminated a culture dish containing staphylococci, he had never heard of Duchesne or his work. Such contamination was a common occurrence in the bacteriological laboratory, but Fleming was the first to recognize its antibacterial effect. Eleven years later Chain and Florey, working at the University of Oxford, isolated and purified penicillin. Then in 1941 penicillin was tested on patients suffering from severe bacterial infections, with dramatic results. World War II interrupted penicillin research in Britain, but workers in the U.S. went on to develop methods for the mass production and stabilization of the drug.

For their work on penicillin Fleming, Chain and Florey shared the 1945 Nobel prize for physiology and medicine. In September of that year Fleming gave a speech at the Academy of Lyons and mentioned the work of Duchesne, which by that time was known to him. He said that whereas he had noticed the antibacterial effects of *Penicillium* by chance, Duchesne had done so by methodical investigation. Fleming's contribution was nonetheless the crucial one. As Francis Darwin, the botanist son of Charles Darwin, observed: "In science the credit goes to the man who convinces the world, not to the man to whom the idea first occurs."

The Acquisition of Language

How do children learn to speak? It seems they do so in a highly methodical way: they break the language down into its simplest parts and develop the rules they need to put the parts together

by Breyne Arlene Moskowitz

An adult who finds herself in a group of people speaking an unfamiliar foreign language may feel quite uncomfortable. The strange language sounds like gibberish: mysterious strings of sound, rising and falling in unpredictable patterns. Each person speaking the language knows when to speak, how to construct the strings and how to interpret other people's strings, but the individual who does not know anything about the language cannot pick out separate words or sounds, let alone discern meanings. She may feel overwhelmed, ignorant and even childlike. It is possible that she is returning to a vague memory from her very early childhood, because the experience of an adult listening to a foreign language comes close to duplicating the experience of an infant listening to the "foreign" language spoken by everyone around her. Like the adult, the child is confronted with the task of learning a language about which she knows nothing.

The task of acquiring language is one for which the adult has lost most of her aptitude but one the child will perform with remarkable skill. Within a short span of time and with almost no direct instruction the child will analyze the language completely. In fact, although many subtle refinements are added between the ages of five and 10, most children have completed the greater part of the basic language-acquisition process by the age of five. By that time a child will have dissected the language into its minimal separable units of sound and meaning; she will have discovered the rules for recombining sounds into words, the meanings of individual words and the rules for recombining words into meaningful sentences, and she will have internalized the intricate patterns of taking turns in dialogue. All in all she will have established herself linguistically as a full-fledged member of a social community, informed about the most subtle details of her native language as it is spoken in a wide variety of situations.

The speed with which children accomplish the complex process of language acquisition is particularly impressive. Ten linguists working full time for 10 years to analyze the structure of the English language could not program a computer with the ability for language acquired by an average child in the first 10 or even five years of life. In spite of the scale of the task and even in spite of adverse conditions—emotional instability, physical disability and so on—children learn to speak. How do they go about it? By what process does a child learn language?

What Is Language?

In order to understand how language is learned it is necessary to understand what language is. The issue is confused by two factors. First, language is learned in early childhood, and adults have few memories of the intense effort that went into the learning process, just as they do not remember the process of learning to walk. Second, adults do have conscious memories of being taught the few grammatical rules that are prescribed as "correct" usage, or the norms of "standard" language. It is difficult for adults to dissociate their memories of school lessons from those of true language learning, but the rules learned in school are only the conventions of an educated society. They are arbitrary finishing touches of embroidery on a thick fabric of language that each child weaves for herself before arriving in the English teacher's classroom. The fabric is grammar: the set of rules that describe how to structure language.

The grammar of language includes rules of phonology, which describe how to put sounds together to form words; rules of syntax, which describe how to put words together to form sentences; rules of semantics, which describe how to interpret the meaning of words and sentences, and rules of pragmatics, which describe how to participate in a conversation, how to sequence sentences and how to anticipate the information needed by an interlocutor. The internal grammar each adult has constructed is identical with that of every other adult in all but a few superficial details. Therefore each adult can create or understand an infinite number of sentences she has never heard before. She knows what is acceptable as a word or a sentence and what is not acceptable, and her judgments on these issues concur with those of other adults. For example, speakers of English generally agree that the sentence "Ideas green sleep colorless furiously" is ungrammatical and that the sentence "Colorless green ideas sleep furiously" is grammatical but makes no sense semantically. There is similar agreement on the grammatical relations represented by word order. For example, it is clear that the sentences "John hit Mary" and "Mary hit John" have different meanings although they consist of the same words, and that the sentence "Flying planes can be dangerous" has two possible meanings. At the level of individual words all adult speakers can agree that "brick" is an English word, that "blick" is not an English word but could be one (that is, there is an accidental gap in the adult lexicon, or internal vocabulary) and that "bnick" is not an English word and could not be one.

How children go about learning the grammar that makes communication possible has always fascinated adults, particularly parents, psychologists and investigators of language. Until recently diary keeping was the primary method of study in this area. For example, in 1877 Charles Darwin published an account of his son's development that includes notes on language learning. Unfortunately most of the diarists used inconsistent or incomplete notations to record what they heard (or what they thought they heard), and most of the diaries were only partial listings of emerging types of sentences with inadequate information on developing word meanings. Although the very best of them, such as W. F. Leopold's classic *Speech Development of a Bilingual Child,* continue to be a rich resource for con-

CHILDREN'S SPEECH IS STUDIED to determine what grammatical rules, which describe how language is structured, they have developed. The author, shown here recording the language output of two young children, works with children in their homes so that their speech is as unconstrained as possible. The search for the regularities in children's language has revealed that in any area of language acquisition they follow the same basic procedure: hypothesizing rules, trying them out and then modifying them. Children formulate the most general rules first and apply them across the board; narrower rules are added later, with exceptions and highly irregular forms. Examples discussed in article concern children learning English, but same process has been observed in children learning other languages.

temporary investigators, advances in audio and video recording equipment have made modern diaries generally much more valuable. In the 1960's, however, new discoveries inspired linguists and psychologists to approach the study of language acquisition in a new, systematic way, oriented less toward long-term diary keeping and more toward a search for the patterns in a child's speech at any given time.

An event that revolutionized linguistics was the publication in 1957 of Noam Chomsky's *Syntactic Structures*. Chomsky's investigation of the structure of grammars revealed that language systems were far deeper and more complex than had been suspected. And of course if linguistics was more complicated, then language learning had to be more complicated. In the 21 years since the publication of *Syntactic Structures* the disciplines of linguistics and child language have come of age. The study of the acquisition of language has benefited not only from the increasingly sophisticated understanding of linguistics but also from the improved understanding of cognitive development as it is related to language. The improvements in recording technology have made experimentation in this area more reliable and more detailed, so that investigators framing new and deeper questions are able to accurately capture both rare occurrences and developing structures.

The picture that is emerging from the more sophisticated investigations reveals the child as an active language learner, continually analyzing what she hears and proceeding in a methodical, predictable way to put together the jigsaw puzzle of language. Different children learn language in similar ways. It is not known how many processes are involved in language learning, but the few that have been observed appear repeatedly, from child to child and from language to language. All the examples I shall discuss here concern children who are learning English, but identical processes have been observed in children learning French, Russian, Finnish, Chinese, Zulu and many other languages.

Children learn the systems of grammar—phonology, syntax, semantics, lexicon and pragmatics—by breaking each system down into its smallest combinable parts and then developing rules for combining the parts. In the first two years of life a child spends much time working on one part of the task, disassembling the language to find the separate sounds that can be put together to form words and the separate words that can be put together to form sentences. After the age of two the basic process continues to be refined, and many more sounds and words are produced. The other part of language acquisition—developing rules for combining the basic elements of language—is carried out in a very methodical way: the most general rules are hypothesized first, and as time passes they are successively narrowed down by the addition of more precise rules applying to a more restricted set of sentences. The procedure is the same in any area of language learning, whether the child is acquiring syntax or phonology or semantics. For example, at the earliest stage of acquiring negatives a child does not have at her command the same range of negative structures that an adult does. She has constructed only a single very general rule: Attach "no" to the beginning of any sentence constructed by the other rules of grammar. At this stage all negative sentences will be formed according to that rule.

Throughout the acquisition process a child continually revises and refines the rules of her internal grammar, learning increasingly detailed subrules until she achieves a set of rules that enables her to create the full array of complex, adult sentences. The process of refinement continues at least until the age of 10 and probably considerably longer for most children. By the time a child is six or seven, however, the changes in her grammar may be so subtle and sophisticated that they go unnoticed. In general children approach language learning economically, devoting their energy to broad issues before dealing with specific ones. They cope with clear-cut questions first and sort out the details later, and they may adopt any one of a variety of methods for circumventing details of a language system they have not yet dealt with.

Prerequisites for Language

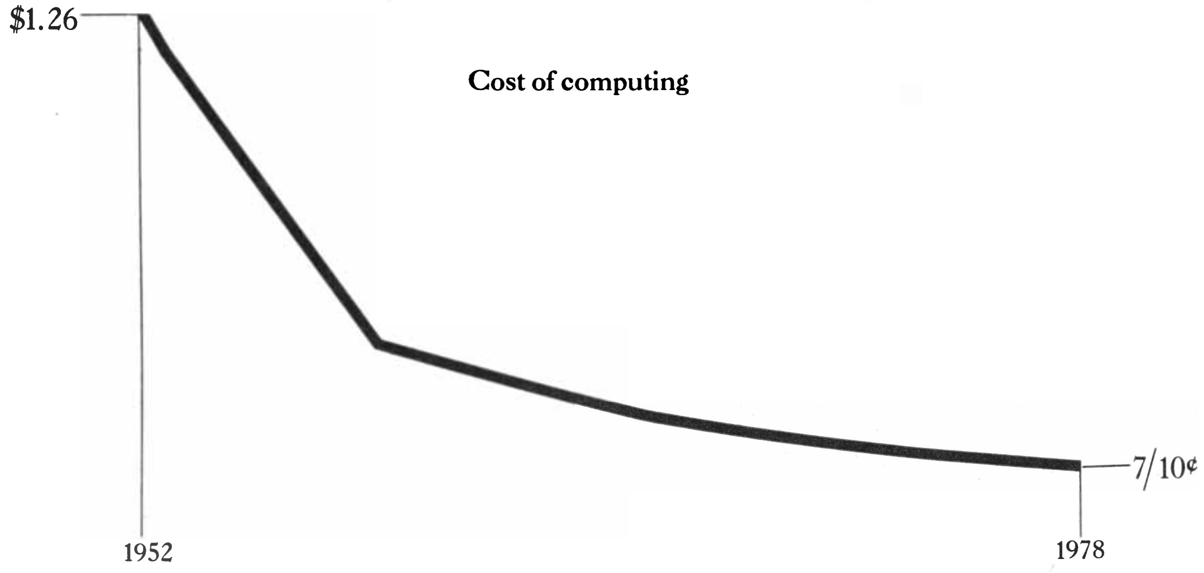
Although some children verbalize much more than others and some increase the length of their utterances much faster than others, all children overgeneralize a single rule before learning to apply it more narrowly and before constructing other less widely applicable rules, and all children speak in one-word sentences before they speak in two-word sentences. The similarities in language learning for different children and different languages are so great that many linguists have believed at one time or another that the human brain is preprogrammed for language learning. Some linguists continue to believe language is innate and only the surface details of the particular language spoken in a child's environment need to be learned. The speed with which children learn language gives this view much appeal. As more parallels between language and other areas of cognition are revealed, however, there is greater reason to believe any language specialization that exists in the child is only one aspect of more general cognitive abilities of the brain.

Whatever the built-in properties the brain brings to the task of language learning may be, it is now known that a child who hears no language learns no language, and that a child learns only the language spoken in her environment. Most infants coo and babble during the first six months of life, but congenitally deaf children have been observed to cease babbling after six months, whereas normal infants continue to babble. A child does not learn language, however, simply by hearing it spoken. A boy with normal hearing but with deaf parents who communicated by the American Sign Language was exposed to television every day so that he would learn English. Because the child

(1)	BOY	CAT	MAN	HOUSE	FOOT FEET
(2)			MEN		
(3)	BOYS	CATS	MANS	HOUSE	FOOTS FEETS
(4)	BOYSəZ	CATSəZ CATəZ	MANSəZ MENəZ	HOUSəZ	FOOTSəZ FEETSəZ
(5)	BOYS	CATS	MANS	HOUSES	FEETS
(6)	BOYS	CATS	MEN	HOUSES	FEET

SORTING OUT OF COMPETING PRONUNCIATIONS that results in the correct plural forms of nouns takes place in the six stages shown in this illustration. Children usually learn the singular forms of nouns first (*1*), although in some cases an irregular plural form such as "feet" may be learned as a singular or as a free variant of a singular. Other irregular plurals may appear for a brief period (*2*), but soon they are replaced by plurals made according to the most general rule possible: To make a noun plural add the sound "s" or "z" to it (*3*). Words such as "house" or "rose," which already end in an "s"- or "z"-like sound, are usually left in their singular forms at this stage. When words of this type do not have irregular plural forms, adults make them plural by adding an "əz" sound. (The vowel "ə" is pronounced like the unstressed word "a.") Some children demonstrate their mastery of this usage by tacking "əz" endings indiscriminately onto nouns (*4*). That stage is brief and use of the ending is quickly narrowed down (*5*). At this point only irregular plurals remain to be learned, and since no new rule-making is needed, children may go on to harder problems and leave final stage (*6*) for later.

Prices keep going up. Information costs keep going down.



The chart shows it all. In the face of a relentless rise in prices, one cost keeps dropping dramatically: information technology.

A set of calculations that cost $1.26 to do on an IBM computer in 1952 can be done today for 7/10ths of a cent.

That's 180 times less. (Compared to the buying power of a 1952 dollar, it's really over 400 times less.)

Why has the information technology industry so successfully bucked the tide of rising prices?

For one thing, it's a young industry. And being young means being innovative.

Here's one example: the computing power of a machine which filled a large room 25 years ago is contained in circuits that you can hold in your hand today. And the computation speeds are over a thousand times faster.

These and other advances come from IBM and hundreds of other companies in the information technology industry.

With every innovative advance, and every resulting reduction in computing costs, the advantages of information technology become available to more and more people. Technology which increases productivity to help slow the pace of rising costs.

Innovation. Productivity. Helping to fight inflation.

IBM®

Helping put information to work for people

(1)	WALK	PLAY	NEED	COME	GO
(2)				CAME	WENT
(3)	WALKED	PLAYED	NEED	COMED	GOED
(4)	WALKEDəD	PLAYEDəD	NEEDəD	CAMEDəD COMEDəD	GOED WENTəD
(5)	WALKED	PLAYED	NEEDED	COMED	GOED
(6)	WALKED	PLAYED	NEEDED	CAME	WENT

DEVELOPMENT OF PAST-TENSE FORMS OF VERBS also takes place in six stages. After the present-tense forms are learned (*1*) irregular past-tense forms may appear briefly (*2*). The first and most general rule that is postulated is: To put a verb into the past tense add a "t" or "d" sound (*3*). In adult speech verbs such as "want" or "need," which already end in a "t" or "d" sound, are put into the past tense by adding "əd" sound. Many children go through brief stage in which they add "əd" endings to any existing verb forms (*4*). Once the use of "əd" ending has been narrowed down (*5*), only irregular past-tense forms remain to be learned (*6*).

was asthmatic and was confined to his home he interacted only with people at home, where his family and all their visitors communicated in sign language. By the age of three he was fluent in sign language but neither understood nor spoke English. It appears that in order to learn a language a child must also be able to interact with real people in that language. A television set does not suffice as the sole medium for language learning because, even though it can ask questions, it cannot respond to a child's answers. A child, then, can develop language only if there is language in her environment and if she can employ that language to communicate with other people in her immediate environment.

Caretaker Speech

In constructing a grammar children have only a limited amount of information available to them, namely the language they hear spoken around them. (Until about the age of three a child models her language on that of her parents; afterward the language of her peer group tends to become more important.) There is no question, however, that the language environments children inhabit are restructured, usually unintentionally, by the adults who take care of them. Recent studies show that there are several ways caretakers systematically modify the child's environment, making the task of language acquisition simpler.

Caretaker speech is a distinct speech register that differs from others in its simplified vocabulary, the systematic phonological simplification of some words, higher pitch, exaggerated intonation, short, simple sentences and a high proportion of questions (among mothers) or imperatives (among fathers). Speech with the first two characteristics is formally designated Baby Talk. Baby Talk is a subsystem of caretaker speech that has been studied over a wide range of languages and cultures. Its characteristics appear to be universal: in languages as diverse as English, Arabic, Comanche and Gilyak (a Paleo-Siberian language) there are simplified vocabulary items for terms relating to food, toys, animals and body functions. Some words are phonologically simplified, frequently by the duplication of syllables, as in "wawa" for "water" and "choo-choo" for "train," or by the reduction of consonant clusters, as in "tummy" for "stomach" and "scambled eggs" for "scrambled eggs." (Many types of phonological simplification seem to mimic the phonological structure of an infant's own early vocabulary.)

Perhaps the most pervasive characteristic of caretaker speech is its syntactic simplification. While a child is still babbling, adults may address long, complex sentences to her, but as soon as she begins to utter meaningful, identifiable words they almost invariably speak to her in very simple sentences. Over the next few years of the child's language development the speech addressed to her by her caretakers may well be describable by a grammar only six months in advance of her own.

The functions of the various language modifications in caretaker speech are not equally apparent. It is possible that higher pitch and exaggerated intonation serve to alert a child to pay attention to what she is hearing. As for Baby Talk, there is no reason to believe the use of phonologically simplified words in any way affects a child's learning of pronunciation. Baby Talk may have only a psychological function, marking speech as being affectionate. On the other hand, syntactic simplification has a clear function. Consider the speech adults address to other adults; it is full of false starts and long, rambling, highly complex sentences. It is not surprising that elaborate theories of innate language ability arose ined the speech adults addressed to adults and assumed that the speech addressed to children was similar. Indeed, it is hard to imagine how a child could derive the rules of language from such input. The wide study of caretaker speech conducted over the past eight years has shown that children do not face this problem. Rather it appears they construct their initial grammars on the basis of the short, simple, grammatical sentences that are addressed to them in the first year or two they speak.

Correcting Language

Caretakers simplify children's language-analysis task in other ways. For example, adults talk with other adults about complex ideas, but they talk with children about the here and now, minimizing discussion of feelings, displaced events and so on. Adults accept children's syntactic and phonological "errors," which are a normal part of the acquisition process. It is important to understand that when children make such errors, they are not producing flawed or incomplete replicas of adult sentences; they are producing sentences that are correct and grammatical with respect to their own current internalized grammar. Indeed, children's errors are essential data for students of child language because it is the consistent departures from the adult model that indicate the nature of a child's current hypotheses about the grammar of language. There are a number of memorized, unanalyzed sentences in any child's output of language. If a child says, "Nobody likes me," there is no way of knowing whether she has memorized the sentence intact or has figured out the rules for constructing the sentence. On the other hand, a sentence such as "Nobody don't like me" is clearly not a memorized form but one that reflects an intermediate stage of a developing grammar.

Since each child's utterances at a particular stage are from her own point of view grammatically correct, it is not surprising that children are fairly impervious to the correction of their language by adults, indeed to any attempts to teach them language. Consider the boy who lamented to his mother, "Nobody don't like me." His mother seized the opportunity to correct him, replying, "Nobody likes me." The child repeated his original version and the mother her modified one a total of eight times until in desperation the mother said, "Now listen carefully! Nobody likes me." Finally her son got the idea and dutifully replied, "Oh! Nobody don't likes me." As the example demonstrates, children do not always understand exactly what it is the adult is correcting. The information the adult is trying to impart may be at odds with the information in the child's head, namely the rules the child

Technology and overregulation: Or, why our standard of living might not get better.

Determining exactly how much government should regulate American life and industry is an extremely difficult problem. In our past, government intervention was spawned by serious and genuine desires to protect the public good against threatened erosion of the quality of American life. Regulation, then, was intended to *improve* our standard of life by intelligent control.

Today the pendulum of regulation has swung too far. The results of overregulation have become as much a threat to the public good as the original evils they were intended to exorcise.

Overregulation now punishes the public more than it protects.

Today, 87 government agencies have been created to regulate some aspect of business. They regulate product safety, food and package labels, and advertising. They establish hiring, firing, and working conditions. They control the environment, speed limits, and community relations.

As the noose of overregulation tightens, it threatens to strangle creativity and invention—and, therefore, productivity and increased employment. To discourage risk and investment in capital expansion. To discourage increasing investment in research and development. To erode our standard of living. And, ultimately, to stifle progress.

Government overregulation doesn't dampen inflation. It fuels it.

During this fiscal year, Professor Murray Weidenbaum of Washington University estimates that compliance with federal regulations will cost nearly $103 billion, 20% of the entire federal budget. Or about $440 for every U.S. citizen.

Put another way, current regulations increase the price of a new house by $1500 to $2500 and the price of an average new car by $666.

Professor Weidenbaum points out that business must invest about $10 billion in new capital spending merely to meet government regulations each year.

It is expensive, time-consuming, and wasteful to do business in America today.

Overregulation reduces the amount of capital and resources available for the

development and extension of new technologies and higher productivity.

But there is a more subtle effect. Since regulations tend to be so complex, comprehensive, and contradictory, meaningful technological development isn't likely to happen. Companies are so confused and so uncertain whether or not a new process or technology will meet existing or future regulations that they prefer to wait for an age of clarity and rely on more primitive, more proven technologies that simply maintain the status quo.

We must solve our problems—not regulate them into more serious problems.

Economic freedom—the free enterprise system—is still a far more effective arbiter of constituency needs than the tangled bureaucratic maze on the banks of the Potomac. Our competitive economic system—if allowed to work—will work. But it must be given the opportunity.

We do not suggest doing away with all regulation. Only those regulations and agencies that are conflicting, unnecessary, and counterproductive. And the regulators who sanctimoniously believe that they, and they alone, are the last, best hope of the public welfare.

Unless the regulatory house is thoroughly cleaned, the public may become so contemptuous of "Big Brother" government that the regulatory process will cease to be effective.

Fortunately, attitudes are changing. Both business and Congress are beginning to do something about overregulation. But there is a good deal more to be done.

1. **We must eliminate conflicts within the regulatory process itself.**
2. **We need to eliminate overlapping regulatory jurisdiction.**
3. **We need to stop trying to regulate everything in existence and concentrate on those abuses that threaten the public good—realistically.**
4. **We need to determine the cost-benefit effectiveness of the regulatory process.**
5. **We need to place "checks and balances" on the regulators themselves.**

But before we do so, we must understand that tinkering is not the answer. We cannot look at only the worst regulations on a piecemeal basis. We cannot try to regulate the regulators. The problem is the system and the process. And that is where we all should begin.

Business, too, must play a constructive role.

Business must take the initiative and help define the difference between regulation that is necessary and overregulation. Business must also better regulate itself, removing the opportunities and need for government intervention and regulation. It is not too late to undo the damage that overregulation has wrought. For America's businessmen have the courage, creativity, knowledge, and ability to balance the scales.

It really is not an option. Something that Thoreau wrote in 1848 now seems alarmingly prophetic: "If we are left solely to the wordy wit of legislators in Congress for our guidance, uncorrected by the reasonable experience and reasonable complaints of its people, America will not long retain her rank among nations." What we need now is a unified voice of resistance, coupled with a sincere commitment to technological progress. And a better standard of living in the future.

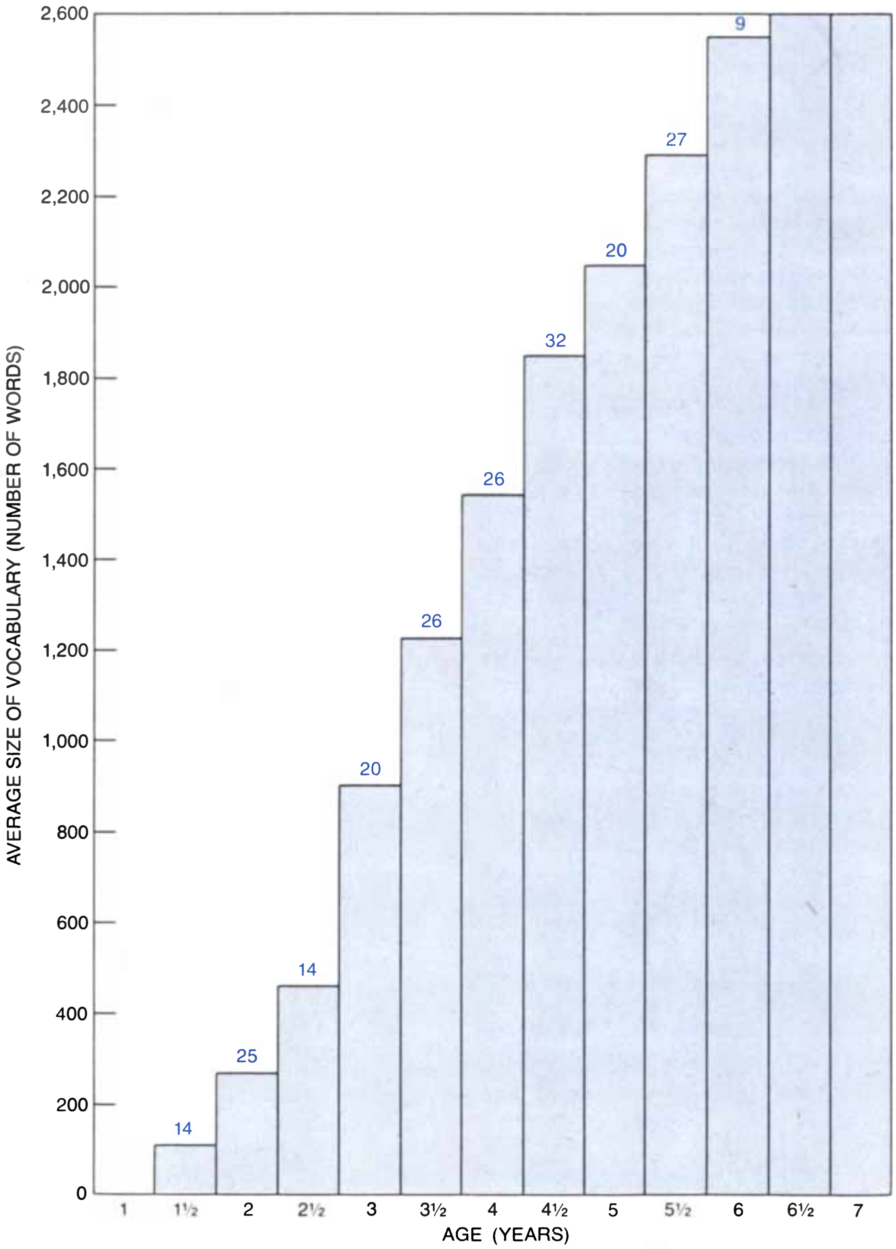
Science and technology can solve many problems. If they don't, what else will?

Gould is an electrical and industrial products company committed to growth through technology. This message is a condensation of a 16-page White Paper, "Technology and Overregulation." For the complete text, write Gould Inc., Dept. S10-11, 10 Gould Center, Rolling Meadows, IL 60008.

GOULD

is postulating for producing language. The surface correction of a sentence does not give the child a clue about how to revise the rule that produced the sentence.

It seems to be virtually impossible to speed up the language-learning process. Experiments conducted by Russian investigators show that it is extremely difficult to teach children a detail of language more than a few days before they would learn it themselves. Adults sometimes do, of course, attempt to teach children rules of language, expecting them to learn by imitation, but Courtney B. Cazden of Harvard University found that children benefit less from frequent adult correction of their errors than from true conversational interaction. Indeed, correcting errors can interrupt that interaction, which is, after all, the function of language. (One way children may try to secure such interaction is by asking "Why?" Children go through a stage of asking a question repeatedly. It serves to keep the conversation going, which may be the child's real aim. For example, a two-and-a-half-year-old named Stanford asked "Why?" and was given the nonsense answer: "Because the moon is made of green cheese." Although the response was not at all germane to the conversation, Stanford was happy with it and again asked "Why?" Many silly answers later the adult had tired of the conversation but Stanford had not. He was clearly not seeking information. What he needed was to practice the form of social conversation before dealing with its func-



CHILDREN'S AVERAGE VOCABULARY SIZE increases rapidly between the ages of one and a half and six and a half. The number of children tested in each sample age group is shown in color. Data are based on work done by Madorah E. Smith of University of Hawaii.

pose well.)

In point of fact adults rarely correct children's ungrammatical sentences. For example, one mother, on hearing "Tommy fall my truck down," turned to Tommy with "Did you fall Stevie's truck down?" Since imitation seems to have little role in the language-acquisition process, however, it is probably just as well that most adults are either too charmed by children's errors or too busy to correct them.

Practice does appear to have an important function in the child's language-learning process. Many children have been observed purposefully practicing language when they are alone, for example in a crib or a playpen. Ruth H. Weir of Stanford University hid a tape recorder in her son's bedroom and recorded his talk after he was put to bed. She found that he played with words and phrases, stringing together sequences of similar sounds and of variations on a phrase or on the use of a word: "What color . . . what color blanket . . . what color mop . . . what color glass . . . what color TV . . . red ant . . . fire . . . like lipstick . . . blanket . . . now the blue blanket . . . what color TV . . . what color horse . . . then what color table . . . then what color fire . . . here yellow spoon." Children who do not have much opportunity to be alone may use dialogue in a similar fashion. When Weir tried to record the bedtime monologues of her second child, whose room adjoined that of the first, she obtained through-the-wall conversations instead.

The One-Word Stage

The first stage of child language is one in which the maximum sentence length is one word; it is followed by a stage in which the maximum sentence length is two words. Early in the one-word stage there are only a few words in a child's vocabulary, but as months go by her lexicon expands with increasing rapidity. The early words are primarily concrete nouns and verbs; more abstract words such as adjectives are acquired later. By the time the child is uttering two-word sentences with some regularity, her lexicon may include hundreds of words.

When a child can say only one word at a time and knows only five words in all, choosing which one to say may not be a complex task. But how does she decide which word to say when she knows 100 words or more? Patricia M. Greenfield of the University of California at Los Angeles and Joshua H. Smith of Stanford have suggested that an important criterion is informativeness, that is, the child selects a word reflecting what is new in a particular situation. Greenfield and Smith also found that a newly acquired word is first used for naming and only later for asking for something.

Superficially the one-word stage

STAGE 1
No . . . wipe finger.
No a boy bed.
No singing song.
No the sun shining.
No money.
No sit there.
No play that.
No fall!
Not . . . fit.
Not a teddy bear.
More . . . no.
Wear mitten no.

STAGE 2
I can't catch you.
I can't see you.
We can't talk.
You can't dance.
I don't want it.
I don't like him.
I don't know his name.
No pinch me.
Book say no.
Touch the snow no.
This a radiator no.
No square . . . is clown.
Don't bite me yet.
Don't leave me.
Don't wake me up . . . again.
He not little, he big.
That no fish school.
That no Mommy.
There no squirrels.
He no bite you.
I no want envelope.
I no taste them.

STAGE 3
We can't make another broom.
I don't want cover on it.
I gave him some so he won't cry.
No, I don't have a book.
I am not a doctor.
It's not cold.
Don't put the two wings on.
I didn't did it.
You didn't caught me.
I not hurt him.
Ask me if I not made mistake.
Because I don't want somebody to wake me up.
I didn't see something.
I isn't . . . I not sad.
This not ice cream.
This no good.
I not crying.
That not turning.
He not taking the walls down.

THREE STAGES in the acquisition of negative sentences were studied by Ursula Bellugi of the Salk Institute for Biological Studies and Edward S. Klima of the University of California at San Diego. They observed that in the first stage almost all negative sentences appear to be formulated according to the rule: Attach "no" or "not" to the beginning of a sentence to make it negative. In the second stage additional rules are postulated that allow the formation of sentences in which "no," "not," "can't" and "don't" appear after the subject and before the verb. In the third stage several issues remain to be worked out, in particular the agreement of pronouns in negative sentences (*dark color*), the inclusion of the forms of the verb "to be" (*gray*) and the correct use of the auxiliary "do" (*white*). In adult speech the auxiliary "do" often carries tense and other functional markings such as the negative; children in third stage may replace it by "not" or use it redundantly to mark tense that is already marked on the main verb.

seems easy to understand: a child says one word at a time, and so each word is a complete sentence with its own sentence intonation. Ten years ago a child in the one-word stage was thought to be learning word meanings but not syntax. Recently, however, students of child language have seen less of a distinction between the one-word stage as a period of word learning and the subsequent period, beginning with the two-word stage, as one of syntax acquisition. It now seems clear that the infant is engaged in an enormous amount of syntactic analysis in the one-word stage, and indeed that her syntactic abilities are reflected in her utterances and in her accurate perception of multiword sentences addressed to her.

Ronald Scollon of the University of Hawaii and Lois Bloom of Columbia University have pointed out independently that important patterns in word choice in the one-word stage can be found by examining larger segments of children's speech. Scollon observed that a 19-month-old named Brenda was able to use a vertical construction (a series of one-word sentences) to express what an adult might say with a horizontal construction (a multiword sentence). Brenda's pronunciation, which is represented phonetically below, was imperfect and Scollon did not understand her words at the time. Later, when he transcribed the tape of their conversation, he heard the sound of a passing car immediately preceding the conversation and was able to identify Brenda's words as follows:

Brenda: "Car [pronounced 'ka']. Car. Car. Car."
Scollon: "What?"
Brenda: "Go. Go."
Scollon: [Undecipherable.]
Brenda: "Bus [pronounced 'baish']. Bus. Bus. Bus. Bus. Bus. Bus. Bus. Bus."
Scollon: "What? Oh, bicycle? Is that what you said?"
Brenda: "Not ['na']."
Scollon: "No?"
Brenda: "Not."
Scollon: "No. I got it wrong."

Brenda was not yet able to combine two words syntactically to express "Hearing that car reminds me that we went on the bus yesterday. No, not on a bicycle." She could express that concept, however, by combining words sequentially. Thus the one-word stage is not just a time for learning the meaning of words. In that period a child is developing hypotheses about putting words together in sentences, and she is already putting sentences together in meaningful groups. The next step will be to put two words together to form a single sentence.

The Two-Word Stage

The two-word stage is a time for experimenting with many binary semantic-syntactic relations such as possessor-possessed ("Mommy sock"), actor-action ("Cat sleeping") and action-object ("Drink soup"). When two-word sentences first began to appear in Brenda's speech, they were primarily of the following forms: subject noun and verb (as in "Monster go"), verb and object (as in "Read it") and verb or noun and location (as in "Bring home" and "Tree down"). She also continued to use vertical constructions in the two-word stage, providing herself with a means of expressing ideas that were still too advanced for her syntax. Therefore once again a description of Brenda's isolated sentences does not show her full abilities at this point in her linguistic development. Consider a later conversation Scollon had with Brenda:

Brenda: "Tape corder. Use it. Use it."
Scollon: "Use it for what?"
Brenda: "Talk. Corder talk. Brenda talk."

Brenda's use of vertical constructions to express concepts she is still unable to encode syntactically is just one example of a strategy employed by children in all areas of cognitive development. As Jean Piaget of the University of Geneva and Dan I. Slobin of the University of California at Berkeley put it, new forms are used for old functions and new functions are expressed by old forms. Long before Brenda acquired the complex syntactic form "Use the tape recorder to record me talking" she was able to use her old forms—two-word sentences and vertical construction—to express the new function. Later, when that function was old, she would develop new forms to express it. The controlled dovetailing of form and function can be observed in all areas of language acquisition. For example, before children acquire the past tense they may employ adverbs of time such as "yesterday" with present-tense verbs to express past time, saying "I do it yesterday" before "I dood it."

Bloom has provided a rare view of an intermediate stage between the one-word and the two-word stages in which the two-word construction—a new form—served only an old function. For several weeks Bloom's daughter Alison uttered two-word sentences all of which included the word "wida." Bloom tried hard to find the meaning of "wida" before realizing that it had no meaning. It was, she concluded, simply a placeholder. This case is the clearest ever reported of a new form preceding new functions. The two-word stage is an important time for practicing functions that will later have expanded forms and practicing forms that will later expand their functions.

Telegraphic Speech

There is no three-word stage in child language. For a few years after the end of the two-word stage children do produce rather short sentences, but the al-

most inviolable length constraints that characterized the first two stages have disappeared. The absence of a three-word stage has not been satisfactorily explained as yet; the answer may have to do with the fact that many basic semantic relations are binary and few are ternary. In any case a great deal is known about the sequential development in the language of the period following the two-word stage. Roger Brown of Harvard has named that language telegraphic speech. (It should be noted that there is no specific age at which a child enters any of these stages of language acquisition and further that there is no particular correlation between intelligence and speed of acquisition.)

Early telegraphic speech is characterized by short, simple sentences made up primarily of content words: words that are rich in semantic content, usually nouns and verbs. The speech is called telegraphic because the sentences lack function "words": tense endings on verbs and plural endings on nouns, prepositions, conjunctions, articles and so on. As the telegraphic-speech stage progresses, function words are gradually added to sentences. This process has possibly been studied more thoroughly than any other in language acquisition, and a fairly predictable order in the addition of function words has been observed. The same principles that govern the order of acquisition of function words in English have been shown to operate in many other languages, including some, such as Finnish and Russian, that express the same grammatical relations with particularly rich systems of noun and verb suffixes.

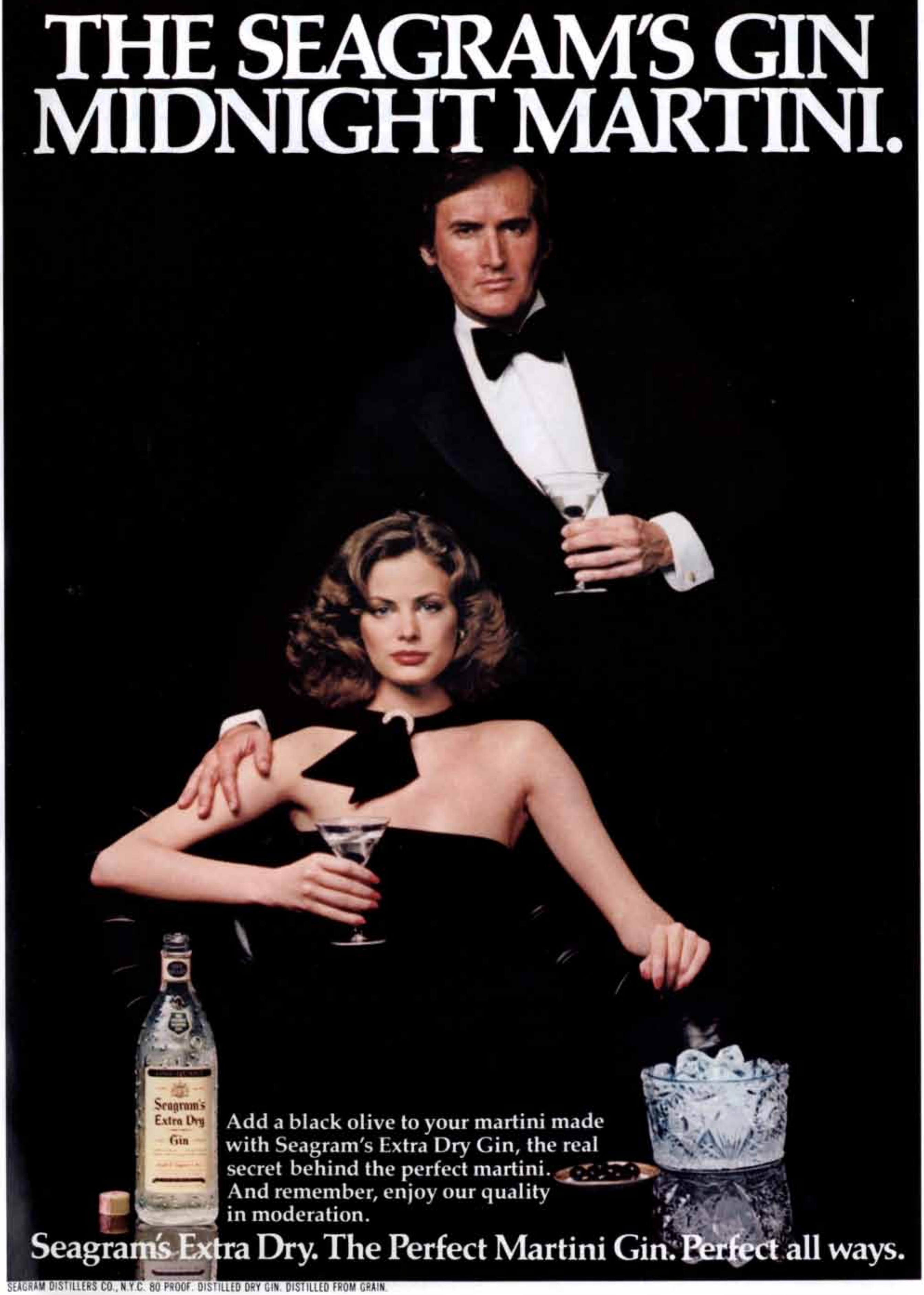
In English many grammatical relations are represented by a fixed word order. For example, in the sentence "The dog followed Jamie to school" it is clear it is the dog that did the following. Normal word order in English requires that the subject come before the verb, and so people who speak English recognize "the dog" as the subject of the sentence. In other languages a noun may be marked as a subject not by its position with respect to the other words in the sentence but by a noun suffix, so that in adult sentences word order may be quite flexible. Until children begin to acquire suffixes and other function words, however, they employ fixed word order to express grammatical relations no matter how flexible adult word order may be. In English the strong propensity to follow word order rigidly shows up in children's interpretations of passive sentences such as "Jamie was followed by the dog." At an early age children may interpret some passive sentences correctly, but by age three they begin to ignore the function words such as "was" and "by" in passive sentences and adopt the fixed word-order interpretation. In other words, since "Jamie" appears before the verb, Jamie is assumed to be the actor, or the noun doing the following.

Function Words

In spite of its grammatical dependence on word order, the English language makes use of enough function words to illustrate the basic principles that determine the order in which such words are acquired. The progressive tense ending "-ing," as in "He going," is acquired first, long before the present-tense third-person singular ending "-s," as in "He goes." The "-s" itself is acquired long before the past tense endings, as in "He goed." Once again the child proves to be a sensible linguist, learning first the tense that exhibits the least variation in form. The "-ing" ending is pronounced only one way, regard-

CHILD'S LEXICAL ITEM	FIRST REFERENTS	OTHER REFERENTS IN ORDER OF OCCURRENCE	GENERAL AREA OF SEMANTIC EXTENSION
MOOI	MOON	CAKE ROUND MARKS ON WINDOWS WRITING ON WINDOWS AND IN BOOKS ROUND SHAPES IN BOOKS TOOLING ON LEATHER BOOK COVERS ROUND POSTMARKS LETTER "O"	SHAPE
BOW-WOW	DOG	FUR PIECE WITH GLASS EYES FATHER'S CUFFLINKS PEARL BUTTONS ON DRESS BATH THERMOMETER	SHAPE
KOTIBAIZ	BARS OF COT	LARGE TOY ABACUS TOAST RACK WITH PARALLEL BARS PICTURE OF BUILDING WITH COLUMNS	SHAPE
BÉBÉ	REFLECTION OF CHILD (SELF) IN MIRROR	PHOTOGRAPH OF SELF ALL PHOTOGRAPHS ALL PICTURES ALL BOOKS WITH PICTURES ALL BOOKS	SHAPE
VOV-VOV	DOG	KITTENS HENS ALL ANIMALS AT A ZOO PICTURE OF PIGS DANCING	SHAPE
ASS	GOAT WITH ROUGH HIDE ON WHEELS	THINGS THAT MOVE: ANIMALS, SISTER, WAGON. . . ALL MOVING THINGS ALL THINGS WITH A ROUGH SURFACE	MOVEMENT TEXTURE
TUTU	TRAIN	ENGINE MOVING TRAIN JOURNEY	MOVEMENT
FLY	FLY	SPECKS OF DIRT DUST ALL SMALL INSECTS CHILD'S OWN TOES CRUMBS OF BREAD A TOAD	SIZE
QUACK	DUCK ON WATER	ALL BIRDS AND INSECTS ALL COINS (AFTER SEEING AN EAGLE ON THE FACE OF A COIN)	SIZE
KOKO	COCKEREL'S CROWING	TUNES PLAYED ON A VIOLIN TUNES PLAYED ON A PIANO TUNES PLAYED ON AN ACCORDION TUNES PLAYED ON A PHONOGRAPH ALL MUSIC MERRY-GO-ROUND	SOUND
DANY	SOUND OF A BELL	CLOCK TELEPHONE DOORBELLS	SOUND

CHILDREN OVERGENERALIZE WORD MEANINGS, using words they acquire early in place of words they have not yet acquired. Eve V. Clark of Stanford University has observed that when a word first appears in a child's lexicon, it refers to a specific object but the child quickly extends semantic domain of word, using it to refer to many other things. Eventually meaning of the word is narrowed down until it coincides with adult usage. Clark found that children most frequently base the semantic extension of a word on shape of its first referent.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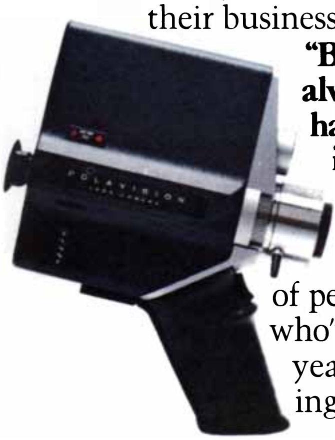

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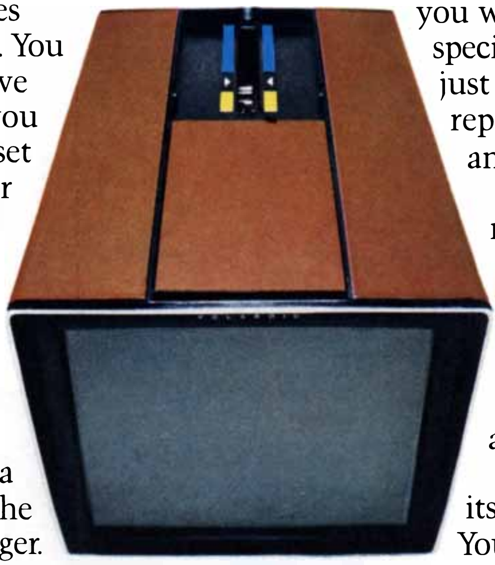

Seeing them is even easier than taking them.

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They began by driving instrumented cars in traffic at different levels of congestion. From a detailed multivariate analysis of the data, they found that a car's fuel consumption in city traffic was related simply and linearly to average trip time (see equation).

$$F = A + BT$$

(valid up to ~ 60 km/h)

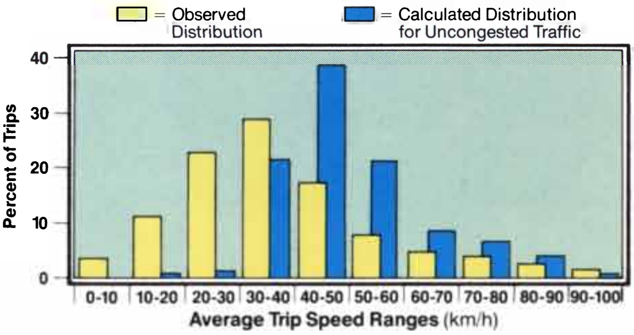
F = fuel consumed per unit distance
A = constant related to average vehicle mass
B = constant related to average idle fuel flow rate
T = average travel time per unit distance

Confirmed in traffic experiments, this relationship suggests that drivers would use less fuel if traffic conditions permitted higher average trip speeds, thus shortening trip times.

What order of fuel savings could be expected?

An analysis was made of trip-speed data collected by GM in Chicago, Denver, Detroit, Los Angeles, New York, San Francisco, and Washington, D.C. Two results: If traffic flow improved so no trip averaged less than a modest 24 km/h (15 mph), a 2.5% fuel saving would result. If the average of all trip speeds equaled that attained in uncongested traffic, 13% would be saved (see graph).

DISTRIBUTION OF SPEEDS IN SEVEN CITIES



Our scientists also developed and validated a computer model to predict travel times throughout a complicated road network. It enables researchers to estimate fuel savings from traffic engineering improvements, car-pooling, staggered work hours, etc.

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to which it is attached. The verb endings "-s" and "-ed," however, vary in their pronunciation: compare "cuts (s)," "cuddles (z)," "crushes (əz)," "walked (t)," "played (d)" and "halted (əd)." (The vowel "ə," called "shwa," is pronounced like the unstressed word "a.") Furthermore, present progressive ("-ing") forms are used with greater frequency than any other tense in the speech children hear. Finally, no verb has an irregular "-ing" form, but some verbs do have irregular third-person present-tense singular forms and many have irregular past-tense forms. (The same pattern of learning earliest those forms that exhibit the least variation shows up much more dramatically in languages such as Finnish and Russian, where the paradigms of inflection are much richer.)

The past tense is acquired after the progressive and present tenses, because the relative time it represents is conceptually more difficult. The future tense ("will" and a verb) is formed regularly in English and is as predictable as the progressive tense, but it is a much more abstract concept than the past tense. Therefore it is acquired much later. In the same way the prepositions "in" and "on" appear earlier than any others, at about the same time as "-ing," but prepositions such as "behind" and "in front of," whose correct usage depends on the speaker's frame of reference, are acquired much later.

It is particularly interesting to note that there are three English morphemes that are pronounced identically but are acquired at different times. They are the plural "-s," the possessive "-s" and the third-person singular tense ending "-s," and they are acquired in the order of has suggested that the explanation of this phenomenon has to do with the complexity of the different relations the morphemes signal: the singular-plural distinction is at the word level, the possessive relates two nouns at the phrase level and the tense ending relates a noun and a verb at the clause level.

The forms of the verb "to be"—"is," "are" and so on—are among the last of the function words to be acquired, particularly in their present-tense forms. Past- and future-tense forms of "to be" carry tense information, of course, but present-tense forms are essentially meaningless, and omitting them is a very sensible strategy for a child who must maximize the information content of a sentence and place priorities on linguistic structures still to be tackled.

Plurals

When there are competing pronunciations available, as in the case of the plural and past tenses, the process of sorting them out also follows a predictable pattern. Consider the acquisition of the English plural, in which six distinct stages can be observed. In English, as in many other (but not all) languages, nouns have both singular and plural forms. Children usually use the singular forms first, both in situations where the singular form would be appropriate and in situations where the plural form would be appropriate. In instances where the plural form is irregular in the adult model, however, a child may not recognize it as such and may use it in place of the singular or as a free variant of the singular. Thus in the first stage of acquisition, before either the concept of a plural are acquired, a child may say "two cat" or point to "one feet."

When plurals begin to appear regularly, the child forms them according to the most general rule of English plural formation. At this point it is the child's overgeneralization of the rule, resulting in words such as "mans," "foots" or "feets," that shows she has hypothesized the rule: Add the sound /s/ or /z/ to the end of a word to make it plural. (The slashes indicate pronounced sounds, which are not to be confused with the letters used in spelling.)

For many children the overgeneralized forms of the irregular nouns are actually the earliest /s/ and /z/ plurals to appear, preceding "boys," "cats" and other regular forms by hours or days. The period of overgeneralization is considered to be the third stage in the acquisition of plurals because for many children there is an intermediate second stage in which irregular plurals such as "men" actually do appear. Concerned parents may regard the change from the second-stage "men" to the third-stage "mans" as a regression, but in reality it demonstrates progress from an individual memorized item to the application of a general rule.

In the third stage the small number of words that already end in a sound resembling /s/ or /z/, such as "house," "rose" and "bush," are used without any plural ending. Adults normally make such words plural by adding the suffix /əz/. Children usually relegate this detail to the remainder pile, to be dealt with at a later time. When they return to the problem, there is often a short fourth stage of perhaps a day, in which the child delightedly demonstrates her

(1) Laura (2:2):
Her want some more.
Her want some more candy.

(2) Laura (2:2):
Where my tiger?
Where my tiger book?

(3) Laura (2:2):
Let's dooz this.
Let's do this.
Let's do this puzzle.

(4) Andrew (2:0):
Put that on.
Andrew put that on.

(5) Andrew (2:1):
All wet.
This shoe all wet.

(6) Benjy (2:3):
Broke it.
Broke it.
Broke it I did.

(7) Jamie (6:0):
Jamie: Why are you doing that?
Mother: What?
Jamie: Why are you writing what I say down?
Mother: What?
Jamie: Why are you writing down what I say?

(8) Jamie (6:3):
Jamie: Who do you think is the importantest kid in the world except me?
Mother: What did you say, Jamie?
Jamie: Who do you think is the specialest kid in the world not counting me?

(9) Jamie (6:6):
Jamie: Who are you versing?
Adult: What?
Jamie: I wanted to know who he was playing against.

(10) Jamie (6:10):
Jamie: I figured something you might like out.
Mother: What did you say?
Jamie: I figured out something you might like.

CHILDREN CORRECT THEIR SPEECH in ways that reflect the improvements they are currently making on their internal grammar. For example, Laura (*1–3*) is increasing the length of her sentences, encoding more information by embellishing a noun phrase. Andrew (*4, 5*) and Benjy (*6*) appear to be adding subjects to familiar verb-phrase sentences. Jamie (*7–10*) seems to be working on much more subtle refinements such as the placement of verb particles, for example the "down" of "writing down." (Each child's age at time of correction is given in years and months.) Corrections shown here were recorded by Judy S. Reilly of University of California at Los Angeles.

criminately onto nouns no matter what sound they end in and no matter how many other plural markings they may already have. A child may wake up one morning and throw herself into this stage with all the zeal of a kitten playing with its first ball of string.

Within a few days the novelty wears off and the child enters a less flamboyant fifth stage, in which only irregular plurals still deviate from the model forms. The rapid progression through the fourth stage does not mean that she suddenly focused her attention on the problem of /əz/ plurals. It is more likely that she had the problem at the back of her mind throughout the third stage. She was probably silently formulating hypotheses about the occurrence of /əz/ and testing them against the plurals she was hearing. Finding the right rule required discovering the phonological specification of the class of nouns that take /əz/ plurals.

Arriving at the sixth and final stage in the acquisition of plurals does not require the formulation of any new rules. All that is needed is the simple memorizing of irregular forms. Being rational, the child relegates such minor details to the lowest-priority remainder pile and turns her attention to more interesting linguistic questions. Hence a five-year-old may still not have entered the last stage. In fact, a child in the penultimate stage may not be at all receptive to being taught irregular plurals. For example, a child named Erica pointed to a picture of some "mouses," and her mother corrected her by saying "mice." Erica and her mother each repeated their own version two more times, and then Erica resolved the standoff by turning to a picture of "ducks." She avoided the picture of the mice for several days. Two years later, of course, Erica was perfectly able to say "mice."

Negative Sentences

One of the pioneering language-acquisition studies of the 1960's was undertaken at Harvard by a research group headed by Brown. The group studied the development in the language of three children over a period of several years. Two members of the group, Ursula Bellugi and Edward S. Klima, looked specifically at the changes in the children's negative sentences over the course of the project. They found that negative structures, like other subsystems of the syntactic component of grammar, are acquired in an orderly, rule-governed way.

When the project began, the forms of negative sentences the children employed were quite simple. It appeared that they had incorporated the following rule into their grammar: To make a sentence negative attach "no" or "not" to the beginning of it. On rare occasions, anticipate the negative, "no" could be attached to the end of a sentence, but negative words could not appear inside a sentence.

In the next stage the children continued to follow this rule, but they had also hypothesized and incorporated into their grammars more complex rules that allowed them to generate sentences in which the negatives "no," "not," "can't" and "don't" appeared after the subject and before the verb. These rules constituted quite an advance over attaching a negative word externally to a sentence. Furthermore, some of the primitive imperative sentences constructed at this stage began with "don't" rather than "no." On the other hand, "can't" never appeared at the beginning of a sentence, and neither "can" nor "do" appeared as an auxiliary, as they do in adult speech: "I can do it." These facts suggest that at this point "can't" and "don't" were unanalyzed negative forms rather than contractions of "cannot" and "do not," but that although "can't" and "don't" each seemed to be interchangeable with "no," they were no longer interchangeable with each other.

In the third stage of acquiring negatives many more details of the negative system had appeared in the children's speech. The main feature of the system that still remained to be worked out was the use of pronouns in negative sentences. At this stage the children said "I didn't see something" and "I don't want somebody to wake me up." The pronouns "somebody" and "something" were later replaced with "nobody" and "nothing" and ultimately with the properly concorded forms "anybody" and "anything."

Many features of telegraphic speech were still evident in the third stage. The form "is" of the verb "to be" was frequently omitted, as in "This no good." In adult speech the auxiliary "do" often functions as a dummy verb to carry tense and other markings; for example, in "I didn't see it," "do" carries the tense and the negative. In the children's speech at this stage "do" appeared occasionally, but the children had not yet figured out its entire function. Therefore in some sentences the auxiliary "do" was omitted and the negative "not" appeared alone, as in "I not hurt him." In other sentences, such as "I didn't did it," the negative auxiliary form of "do" appears to be correct but is actually an unanalyzed, memorized item; at this stage the tense is regularly marked on the main verb, which in this example happens also to be "do."

Many children acquire negatives in the same way that the children in the Harvard study did, but subsequent investigations have shown that there is more than one way to learn a language. Carol B. Lord of U.C.L.A. identified a quite different strategy employed by a

two-year-old named Jennifer. From 24 to 28 months Jennifer used "no" only as a single-word utterance. In order to produce a negative sentence she simply spoke an ordinary sentence with a higher pitch. For example, "I want put it on" spoken with a high pitch meant "I don't want to put it on." Lord noticed that many of the negative sentences adults addressed to Jennifer were spoken with an elevated pitch. Children tend to pay more attention to the beginning and ending of sentences, and in adult speech negative words usually appear in the middle of sentences. With good reason, then, Jennifer seemed to have hypothesized that one makes a sentence negative by uttering it with a higher pitch. Other children have been found to follow the same strategy. There are clearly variations in the hypotheses children make in the process of constructing grammar.

Semantics

Up to this point I have mainly discussed the acquisition of syntactic rules, in part because in the years following the publication of Chomsky's *Syntactic Structures* child-language research in this area flourished. Syntactic rules, which govern the ordering of words in a sentence, are not all a child needs to know about language, however, and after the first flush of excitement over Chomsky's work investigators began to ask questions about other areas of language acquisition. Consider the development of the rules of semantics, which govern the way words are interpreted. Eve V. Clark of Stanford reexamined old diary studies and noticed that the development in the meaning of words during the first several months of the one-word stage seemed to follow a basic pattern.

The first time children in the studies used a word, Clark noted, it seemed to be as a proper noun, as the name of a specific object. Almost immediately, however, the children generalized the word based on some feature of the original object and used it to refer to many other objects. For example, a child named Hildegard first used "tick-tock" as the name for her father's watch, but she quickly broadened the meaning of the word, first to include all clocks, then all watches, then a gas meter, then a firehose wound on a spool and then a bathroom scale with a round dial. Her generalizations appear to be based on her observation of common features of shape: roundness, dials and so on. In general the children in the diary studies overextended meanings based on similarities of movement, texture, size and, most frequently, shape.

As the children progressed, the meanings of words were narrowed down until eventually they more or less coincided with the meanings accepted by adult speakers of the language. The narrowing-down process has not been studied intensively, but it seems likely that the process has no fixed end point. Rather it appears that the meanings of words continue to expand and contract through adulthood, long after other types of language acquisition have ceased.

One of the problems encountered in trying to understand the acquisition of semantics is that it is often difficult to determine the precise meaning a child has constructed for a word. Some interesting observations have been made, however, concerning the development of the meanings of the pairs of words that function as opposites in adult language. Margaret Donaldson and George Balfour of the University of Edinburgh asked children from three to five years old which one of two cardboard trees had "more" apples on it. They asked other children of the same age which tree had "less" apples. (Each child was interviewed individually.) Almost all the children in both groups responded by pointing to the tree with more apples on it. Moreover, the children who had been asked to point to the tree with "less" apples showed no hesitation in choosing the tree with more apples. They did not act as though they did not know the meaning of "less"; rather they acted as if they did know the meaning and "less" meant "more."

Subsequent studies have revealed similar systematic error making in the acquisition of other pairs of opposites such as "same" and "different," "big" and "little," "wide" and "narrow" and "tall" and "short." In every case the pattern of learning is the same: one word of the pair is learned first and its meaning is overextended to apply to the other word in the pair. The first word learned is always the unmarked word of the pair, that is, the word adults use when they do not want to indicate either one of the opposites. (For example, in the case of "wide" and "narrow," "wide" is the unmarked word: asking "How wide is the road?" does not suggest that the road is wide, but asking "How narrow is the road?" does suggest that the road is narrow.)

Clark observed a more intricate pattern of error production in the acquisition of the words "before" and "after." Consider the four different types of sentence represented by (1) "He jumped the gate before he patted the dog," (2) "Before he patted the dog he jumped the gate," (3) "He patted the dog after he jumped the gate" and (4) "After he jumped the gate he patted the dog." Clark found that the way the children she observed interpreted sentences such as these could be divided into four stages.

In the first stage the children disregarded the words "before" and "after" in all four of these sentence types and assumed that the event of the first clause took place before the event of the second clause. With this order-of-mention strategy the first and fourth sentence types were interpreted correctly but the second and third sentence types were not. In the second stage sentences using "before" were interpreted correctly but an order-of-mention strategy was still adopted for sentences that used "after." Hence sentences of the fourth type were interpreted correctly but sentences of the third type were not. In the next stage both the third and the fourth sentence types were interpreted incorrectly, suggesting that the children had adopted the strategy that "after" actually meant "before." Finally, in the fourth stage both "before" and "after" were interpreted appropriately.

It appears, then, that in learning the meaning of a pair of words such as "more" and "less" or "before" and "after" children acquire first the part of the meaning that is common to both words and only later the part of the meaning that distinguishes the two. Linguists have not yet developed satisfactory ways of separating the components of meaning that make up a single word, but it seems clear that when such components can be identified, it will be established that, for example, "more" and "less" have a large number of components in common and differ only in a single component specifying the pole of the dimension. Beyond the studies of opposites there has been little investigation of the period of semantic acquisition that follows the early period of rampant overgeneralization. How children past the early stage learn the meanings of other kinds of words is still not well understood.

Phonology

Just as children overgeneralize word meanings and sentence structures, so do they overgeneralize sounds, using sounds they have learned in place of sounds they have not yet acquired. Just as a child may use the word "not" correctly in one sentence but instead of another negative word in a second sentence, so may she correctly contrast /p/ and /b/ at the beginnings of words but employ /p/ at the ends of words, regardless of whether the adult models end with /p/ or /b/. Children also acquire the details of the phonological system in very regular ways. The ways in which they acquire individual sounds, however, are highly idiosyncratic, and so for many years the patterns eluded diarists, who tended to look only at the order in which sounds were acquired. Jakobson made a major advance in this area by suggesting that it was not individual sounds children acquire in an orderly way but the distinctive features of sound, that is, the minimal differences, or contrasts, between sounds. In other words, when a child begins to contrast /p/ and /b/, she also begins to contrast all the other pairs of sounds that, like /p/ and /b/, differ only in the absence or presence of vocal-cord vibration. In English these pairs include /t/ and /d/, and /k/ and the hard /g/. It is the acquisition of this contrast and not of the six individual sounds that is predictable. Jakobson's extensive examination of the diary data for a wide variety of languages supported his theory. Almost all current work in phonological theory rests on the theory of distinctive features that grew out of his work.

My own recent work suggests that phonological units even more basic than the distinctive features play an important part in the early acquisition process. At an early stage, when there are relatively few words in a child's repertory, unanalyzed syllables appear to be the basic unit of the sound system. By designating these syllables as unanalyzed I mean that the child is not able to separate them into their component consonants and vowels. Only later in the acquisition process does such division into smaller units become possible. The gradual discovery of successively smaller units that can form the basis of the phonological system is an important part of the process.

At an even earlier stage, before a child has uttered any words, she is accomplishing a great deal of linguistic learning, working with a unit of phonological organization even more primitive than the syllable. That unit can be defined in terms of pitch contours. By the late babbling period children already control the intonation, or pitch modulation, contours of the language they are learning. At that stage the child sounds as if she is uttering reasonably long sentences, and adult listeners may have the impression they are not quite catching the child's words. There are no words to catch, only random strings of babbled sounds with recognizable, correctly produced question or statement intonation contours. The sounds may accidentally be similar to some of those found in adult English. These sentence-length utterances are called sentence units, and in the phonological system of the child at this stage they are comparable to the consonant-and-vowel segments, syllables and distinctive features that appear in the phonological systems of later stages. The syllables and segments that appear when the period of word learning begins are in no way related to the vast repertory of babbling sounds. Only the intonation contours are carried over from the babbling stage into the later period.

No matter what language environment a child grows up in, the intonation contours characteristic of adult speech in that environment are the linguistic information learned earliest. Some recent studies suggest that it is possible to identify the language environment of a child from her babbling intonation during the

gest that children can be distinguished at an even earlier age on the basis of whether or not their language environment is a tone language, that is, a language in which words spoken with different pitches are identifiable as different words, even though they may have the same sequence of consonants and vowels. To put it another way, "ma" spoken with a high pitch and "ma" spoken with a low pitch can be as different to someone speaking a tone language as "ma" and "pa" are to someone speaking English. (Many African and Asian languages are tone languages.) Tones are learned very early, and entire tone systems are mastered long before other areas of phonology. The extremely early acquisition of pitch patterns may help to explain the difficulty adults have in learning the intonation of a second language.

Phonetics

There is one significant way in which the acquisition of phonology differs from the acquisition of other language systems. As a child is acquiring the phonological system she must also learn the phonetic realization of the system: the actual details of physiological and acoustic phonetics, which call for the coordination of a complex set of muscle movements. Some children complete the process of learning how to pronounce things earlier than others, but differences of this kind are usually not related to the learning of the phonological system. Brown had what has become a classic conversation with a child who referred to a "fis." Brown repeated "fis," and the child indignantly corrected him, saying "fis." After several such exchanges Brown tried "fish," and the child, finally satisfied, replied, "Yes, fis." It is clear that although the child was still not able to pronounce the distinction between the sounds "s" and "sh," he knew such a systematic phonological distinction existed. Such phonetic muddying of the phonological waters complicates the study of this area of acquisition. Since the child's knowledge of the phonological system may not show up in her speech, it is not easy to determine what a child knows about the system without engaging in complex experimentation and creative hypothesizing.

Children whose phonological system produces only simple words such as "mama" and "papa" actually have a greater phonetic repertory than their utterances suggest. Evidence of that repertory is found in the late babbling stage, when children are working with sentence units and are making a large array of sounds. They do not lose their phonetic ability overnight, but they must constrain it systematically. Going on to the next-higher stage of language learning, the phonological system, is more

SCIENCE/SCOPE

Orbiter's 300 million mile journey to Venus ends, and its scientific mission begins on December 4. Then this first of two Pioneer Venus spacecraft, with its dozen scientific instruments, goes into orbit around the planet. While circling, Orbiter will determine the detailed structure of the upper atmosphere and ionosphere. It will look for variations in the gravitational field, and use remote sensing to survey Venus' atmosphere and surface. A cloud polarimeter will provide visible- and ultraviolet-light pictures resembling those taken of the earth by weather satellites. A Hughes-developed radar mapper will pierce the dense cloud cover to make pictures of Venus' surface.

The spacecraft will orbit for at least one Venusian day (243 earth days). Data obtained should help scientists understand Venus' weather patterns, and provide new insights into causes of the earth's complex weather cycles. Orbiter and its sister ship, Multiprobe, were built by Hughes for NASA's Ames Research Center.

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important to the child than the details of facile pronunciation. Much later, after the phonological system has been acquired, the details of pronunciation receive more attention.

In the period following the babbling period the persisting phonetic facility gets less and less exercise. The vast majority of a child's utterances fail to reflect her real ability to pronounce things accurately; they do, however, reflect her growing ability to pronounce things systematically. (For a child who grows up learning only one language the movements of the muscles of the vocal tract ultimately become so overpracticed that it is difficult to learn new pronunciations during adulthood. On the other hand, people who learn at least two languages in early childhood appear to retain a greater flexibility of the vocal musculature and are more likely to learn to speak an additional language in their adult years without the "accent" of their native language.)

In learning to pronounce, then, a child must acquire a sound system that includes the divergent systems of phonology and phonetics. The acquisition of phonology differs from that of phonetics in requiring the creation of a representation of language in the mind of the child. This representation is necessary because of the abstract nature of the units of phonological structure. From only the acoustic signal of adult language the child must derive successively more abstract phonological units: first intonations, then syllables, then distinctive features and finally consonant-and-vowel segments. There are, for example, few clear segment boundaries in the acoustic signal the child receives, and so the consonant-and-vowel units could hardly be derived if the child had no internal representation of language.

At the same time that a child is building a phonological representation of language she is learning to manipulate all the phonetic variations of language, learning to produce each one precisely and automatically. The dual process of phonetics and phonology acquisition is one of the most difficult in all of language learning. Indeed, although a great deal of syntactic and semantic acquisition has yet to take place, it is usually at the completion of the process of learning to pronounce that adults consider a child to be a full-fledged language speaker and stop using any form of caretaker speech.

Abnormal Language Development

There seems to be little question that the human brain is best suited to language learning before puberty. Foreign languages are certainly learned most easily at that time. Furthermore, it has been observed that people who learn more than one language in childhood have an easier time learning additional

languages in later years. It seems to be extremely important for a child to exercise the language-learning faculty. Children who are not exposed to any learnable language during the crucial years, for example children who are deaf before they can speak, generally grow up with the handicap of having little or no language. The handicap is unnecessary: deaf children of deaf parents who communicate by means of the American Sign Language do not grow up without language. They live in an environment where they can make full use of their language-learning abilities, and they are reasonably fluent in sign language by age three, right on the developmental schedule. Deaf children who grow up communicating by means of sign language have a much easier time learning English as a second language than deaf children in oral-speech programs learning English as a first language.

The study of child language acquisition has made important contributions to the study of abnormal speech development. Some investigators of child language have looked at children whose language development is abnormal in the hope of finding the conditions that are necessary and sufficient for normal development; others have looked at the development of language in normal children in the hope of helping children whose language development is abnormal. It now appears that many of the severe language abnormalities found in children can in some way be traced to interruptions of the normal acquisition process. The improved understanding of the normal process is being exploited to create treatment programs for children with such problems. In the past therapeutic methods for children with language problems have emphasized the memorizing of language routines, but methods now being developed would allow a child to work with her own language-learning abilities. For example, the American Sign Language has been taught successfully to several autistic children. Many of these nonverbal and antisocial children have learned in this way to communicate with therapists, in some cases becoming more socially responsive. (Why sign language should be so successful with some autistic children is unclear; it may have to do with the fact that a sign lasts longer than an auditory signal.)

There are still many questions to be answered in the various areas I have discussed, but in general a great deal of progress has been made in understanding child language over the past 20 years. The study of the acquisition of language has come of age. It is now a genuinely interdisciplinary field where psychologists, neurosurgeons and linguists work together to penetrate the mechanisms of perception and cognition as well as the mechanisms of language.

Rich Clusters of Galaxies

Some 10 percent of all galaxies belong to rich clusters, systems with thousands of members embedded in hot gas. Such a cluster is a gravitational maelstrom with giant galaxies close to its center

by Paul Gorenstein and Wallace Tucker

There appears to be a fundamental tendency in nature for all things of a given class to clump together, thereby forming units of a new class of higher order. In the nonliving world elementary particles clump together to form atoms, atoms to form molecules, atoms and molecules to form stars and planets, and so on up the chain of being to galaxies and clusters of galaxies. At either end of the hierarchy are found the limits of human knowledge. It is possible that subatomic particles are associations of the entities known as quarks and that clusters of galaxies are bound into the still larger associations known as superclusters. Clusters of galaxies are of particular interest because they are the last firmly established level at the top of the hierarchy. In the words of the astronomer Fritz Zwicky, who helped to establish their existence, they are "the last stepping-stone to the study of the universe as a whole." They provide a laboratory several million light-years across for studying the interaction of gas, stars and galaxies on a grand scale. As a result they have attracted the close attention of astronomers observing at radio, light and X-ray wavelengths of the electromagnetic spectrum.

Over the past half century large telescopes have revealed thousands of richly populated clusters, each of which consists of thousands of galaxies made up of tens of billions of stars. In comparison our own galaxy is a member of a very small system known as the local group, consisting of no more than two dozen galaxies, most of them much smaller than ours. Studies of several rich clusters have shown that most of the thousands of galaxies in them are swarming through space at thousands of kilometers per second. The high velocity of these galaxies and their dense distribution in space imply that they are bound together by gravitational forces much greater than those that can be accounted for by the visible mass, that is, by the mass represented by the objects visible on photographic plates.

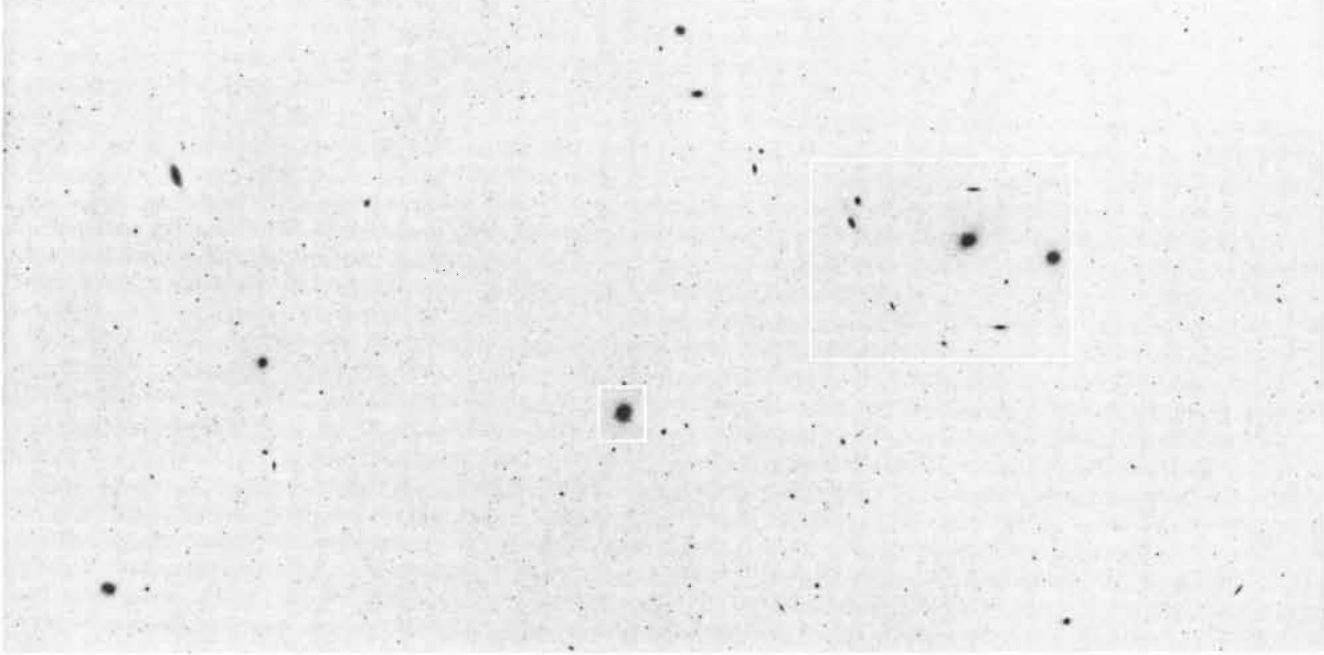
Recent observations at X-ray and radio wavelengths have disclosed that the space between the galaxies in rich clusters is filled by hot gas and that in certain giant elliptical galaxies found at the center of the clusters there have been titanic explosions that have ejected into the hot intergalactic gas vast clouds of high-energy subatomic particles. What causes these explosions? What is the origin of the hot gas? Where is the extra mass that is needed to keep the speeding galaxies from flying apart? Astronomers cannot yet supply definite answers to these questions, but in the past few years the outlines of a picture that shows promise of resolving them have taken shape. According to this picture, the conditions in rich clusters can be understood as resulting from the interaction of gas, stars and galaxies in a gravitational maelstrom generated by the dense concentration of galaxies at the center of the cluster. Quite recent observations have led to the extraordinary suggestion that the giant galaxy M87, located near the center of the large cluster in the constellation Virgo, may have in its nucleus a black hole with a mass equal to that of five billion suns.

Long before it was recognized that what are now called galaxies were "island universes," or independent systems of stars, astronomers noted a tendency for "nebulae" to bunch together in groups. The bunching is apparent in a sky map representing the positions of more than 11,000 nebular objects listed in J. L. E. Dreyer's *New General Catalogue,* published near the end of the 19th century. By the 1920's it was clear that most of the objects listed as nebulas in the catalogue were indeed galaxies, and many are still best known by the NGC number assigned by Dreyer. The detailed surveys that followed in the next decade disclosed that on a large scale the galaxies are distributed uniformly both in angle around the sky and in distance. On the other hand, the apparent clustering of the comparatively nearby galaxies that was evident from the earlier maps of the sky persisted out to much greater distances.

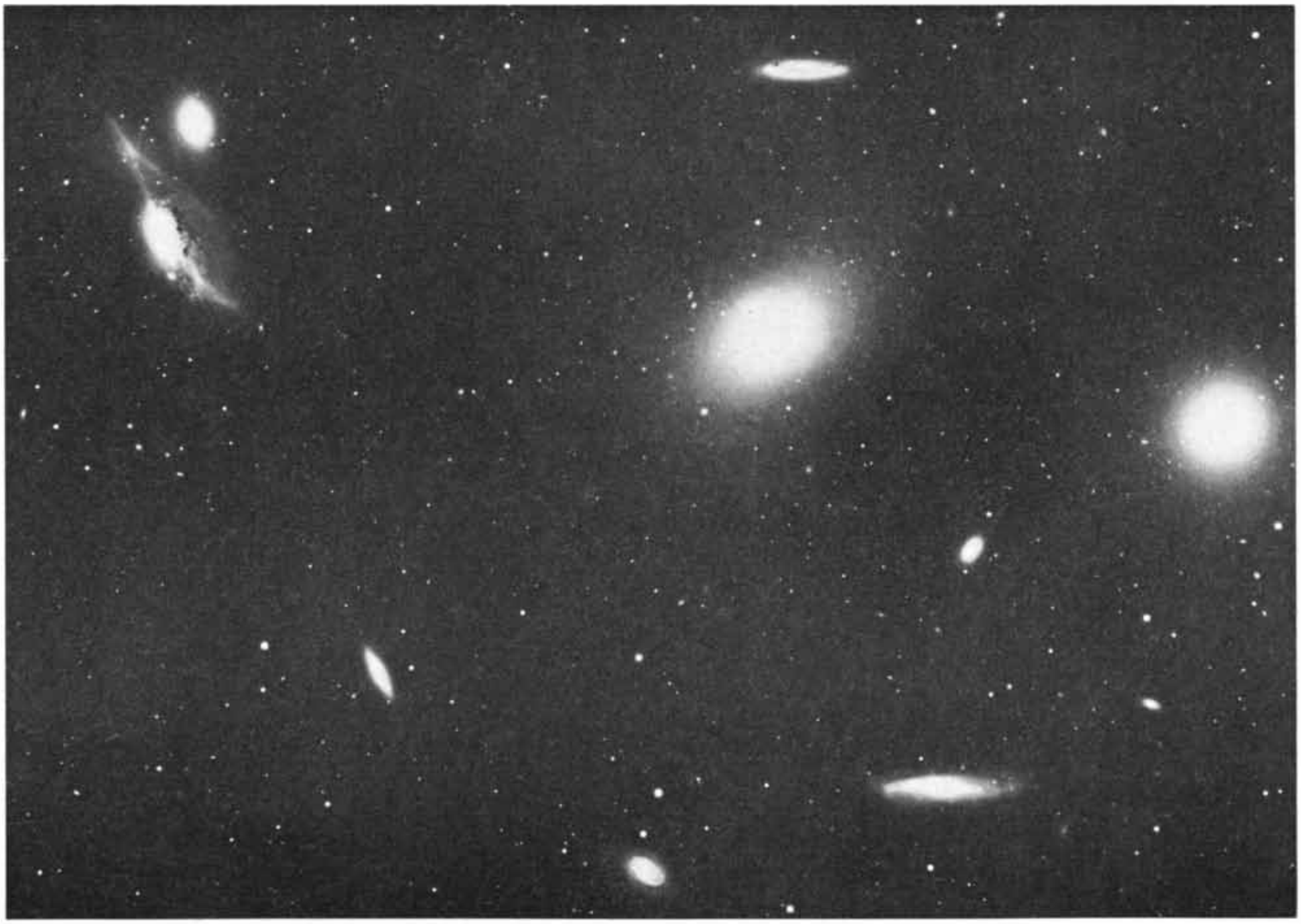
In 1933 Harlow Shapley published a catalogue of 25 clusters of galaxies and proposed that such clusters were not merely coincidences of position but were physical associations arising from evolutionary processes. In the same year Zwicky published a study of the distribution of the galaxies in the large cluster in the constellation Coma Berenices implying that the galaxies were permanently bound by their mutual gravitational attraction. Zwicky pointed out, however, that the amount of mass actually observed in the form of galaxies was not enough to account for the required strength of the gravitational field. The problem of "the missing mass" was therewith introduced into the study of clusters of galaxies.

It is now generally believed that at least half of all the galaxies in the universe are members of a group or a cluster of some size or other, ranging from galaxy-poor groups such as our own to rich clusters consisting of thousands of galaxies. The 20-odd galaxies in the local group lie within a sphere that has a diameter of roughly two million light-years. At opposite ends of the group are our galaxy and the Great Nebula in Andromeda, the galaxy M31. They are large spiral galaxies that together contain about 70 percent of all the mass in the local group. There is much empty space in the group; the probability of our galaxy's ever colliding with the Andromeda galaxy is close to zero. Small groups with much empty space are the commonest type of galactic association. Large clusters and rich clusters, both of which have 1,000 members or more, account for about 10 percent of all galaxies. A rich cluster is defined as a large cluster that has an unusually high density of galaxies at its center.

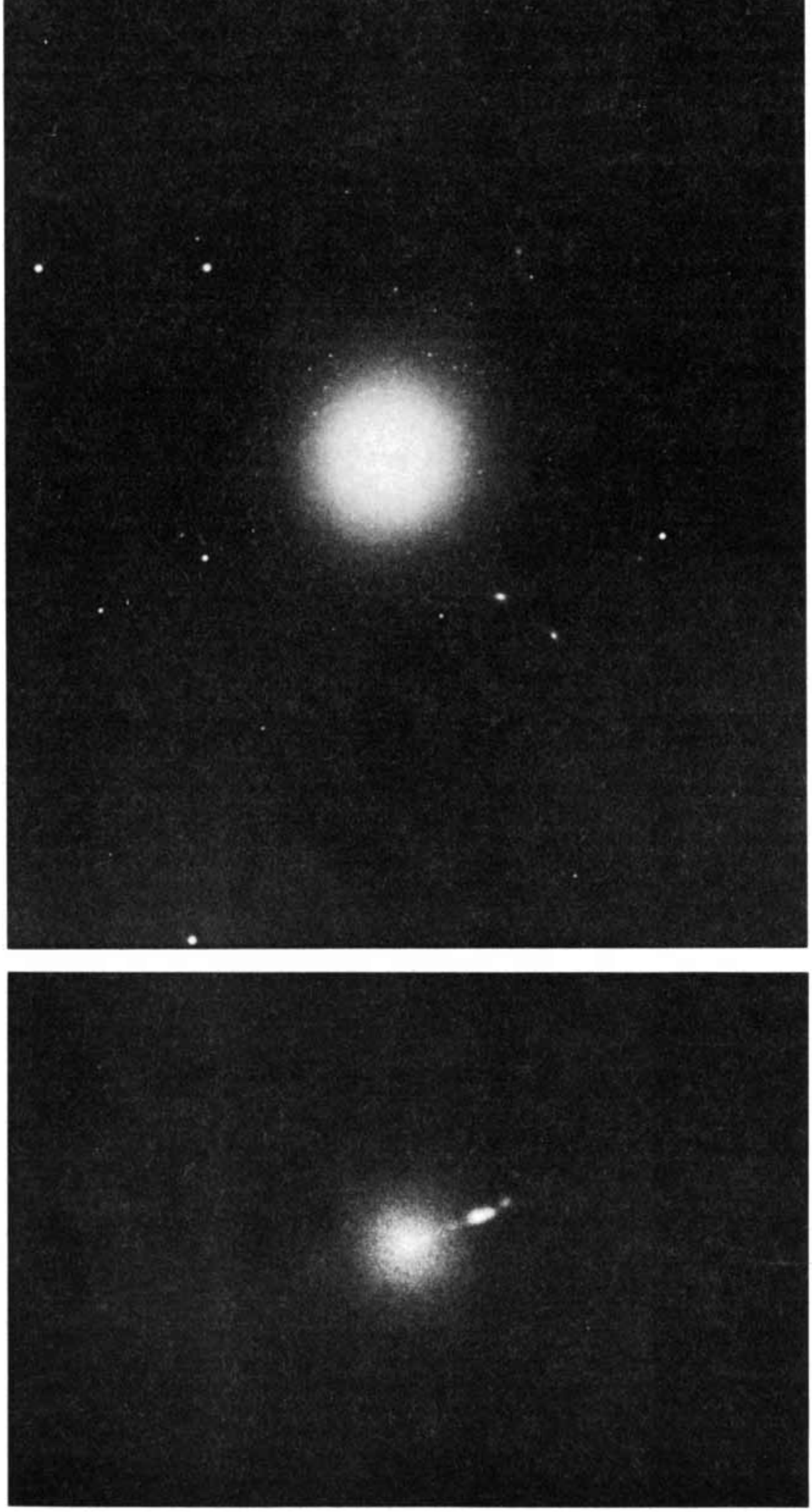
High-energy activity in the form of X-ray and radio emissions is most evident in large clusters. The nearest large cluster is the one in Virgo, about 60 million light-years away. It is irregular in shape and covers about 100 square degrees in the sky; a book of average size held at arm's length would just cover it. It consists of at least 1,000 galaxies, most of them large spiral galaxies and dwarf el-



CLUSTER OF GALAXIES in the constellation Virgo is typical of a large but irregular cluster containing more than 1,000 individual galaxies. In this negative print of a photograph made with the 48-inch Schmidt telescope on Palomar Mountain the galaxies can be recognized by their fuzzy images. The pointlike images are produced by stars within our own galaxy. Only about a fifth of the cluster appears in the photograph, which shows a region some 4.5 degrees across, equivalent to five million light-years at the distance of the Virgo cluster (60 million light-years). The area within the larger rectangle is shown in the photograph at the bottom of the page. The large galaxy within the smaller rectangle is the giant elliptical galaxy M87, which emits strongly in the radio and X-ray regions of the spectrum.



DETAIL OF VIRGO CLUSTER is shown in this positive print of a photograph made with the four-meter telescope at the Cerro Tololo Inter-American Observatory in Chile, operated by Kitt Peak National Observatory. Largest objects are elliptical galaxies M84 and M86.



TWO VIEWS OF M87, the giant elliptical galaxy in the Virgo cluster, reveal two remarkable aspects of one of the brightest galaxies known. The long-exposure photograph at the top, made with the four-meter Cerro Tololo telescope, reveals some of the more than 500 globular clusters that populate the "halo" surrounding the galaxy. Each cluster is a spherical association of more than 100,000 stars. In the much shorter exposure at the bottom, made with the 120-inch telescope at the Lick Observatory, one can see a luminous jet 6,000 light-years long issuing from the center of the galaxy. Recent optical studies suggest the presence of a compact object, possibly a black hole, in the center of the galaxy with a mass five billion times that of the sun.

are giant elliptical galaxies.

The giant elliptical galaxy M87 is three times more luminous than our galaxy, which consists of at least 100 billion stars. Emanating from the nucleus of M87 is a peculiar jetlike feature about 6,000 light-years long, which is a strong source of nonthermal radio and optical emission. "Nonthermal" means that the emitted energy does not have the spectral characteristics of the energy emitted by a hot body. A common source of nonthermal radio and optical emission is energetic electrons traveling in strong magnetic fields.

The generally accepted explanation of the jet is that it was ejected from the nucleus of M87 in a violent explosion or series of explosions that began a million years before the epoch in which the jet is now observed. Strong nonthermal radio and optical radiation, X-ray emission and other evidence of explosive activity are now recognized as being a common feature of many elliptical galaxies and other peculiar astronomical objects, notably the quasars. The origin of such explosive activity, in which energy is often released at a rate a trillion times that of the sun, is one of the major riddles of astronomy today.

X-ray detectors carried above the earth's atmosphere by the *Uhuru* satellite revealed that M87 is enveloped by an X-ray-emitting cloud nearly a million light-years across. The spectrum of the X-ray source was subsequently analyzed by instruments aboard the British *Ariel 5* satellite and by the *OSO-8* satellite of the National Aeronautics and Space Administration. From the presence of certain emission lines of highly ionized iron it can be inferred that the X rays arise from a diffuse gas whose temperature is about 30 million degrees Kelvin (degrees Celsius above absolute zero). At least the X rays, then, are generated by a source that is thermal rather than nonthermal.

If a hot gas is not somehow confined, it tends to expand indefinitely. In the absence of a confining force the gas cloud around M87 would disperse in about 100 million years. Although that may seem like a long time, it is only 1 percent of the total lifetime of the galaxy. To account for the gas cloud as it is now observed there are three possibilities: some force is confining the gas to the galaxy, the gas is being continuously replenished as it expands or the galaxy is at a special point in its history, before the gas has had time to dissipate. The third alternative is possible but rather improbable. The second not only requires an exorbitant amount of energy but also implies that the hot cloud should be spread out in a much larger volume of space than the one it actually occupies. That leaves as the most like-

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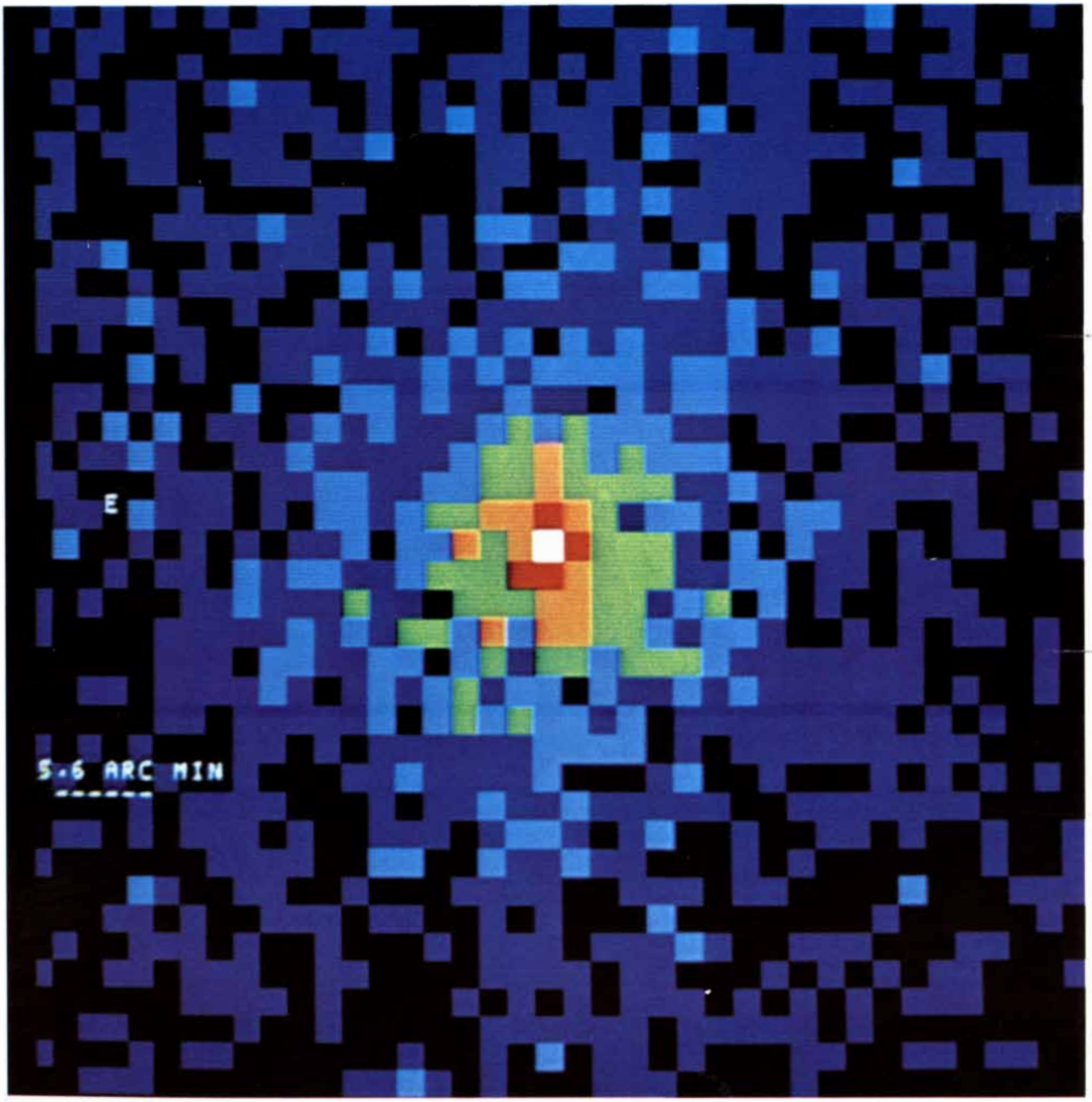
ly explanation confinement by a force, namely gravity.

From the distribution of the X-ray brightness of the surface of the gas one can estimate the distribution of the gas in space. From that distribution the mass needed for gravitational confinement can be estimated to be at least 50 trillion times the mass of the sun. This mass is several hundred times the mass observed in the disk of large spiral galaxies such as ours and the Andromeda galaxy and about 30 times larger than previous estimates of the mass of M87. There is other evidence that supports the conclusion that M87 is an extremely massive galaxy. In 1969 Gerard de Vaucouleurs of the University of Texas at Austin and Halton C. Arp and Francesco Bertola at the Hale Observatories independently reported the detection of a faint optical "halo," or corona, around M87. The halo extends out to distances on the order of 500,000 to a million light-years from the center of the galaxy. Spectral evidence suggests that most of the optical radiation in the halo is coming from stars and not from a hot gas or a cloud of high-energy electrons. For these stars to be bound gravitationally to the galaxy a galactic mass of several tens of trillions of solar masses is required, which is consistent with the estimates derived from the X-ray observations.

The assignment of very large masses



X-RAY HALO AROUND M87 was recorded from a rocket carrying an X-ray telescope that had been designed by one of the authors (Gorenstein) and his colleagues at the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory. In this false-color computer presentation the lighter the color, the higher the X-ray intensity. The area that is covered by the image is about a million light-years across, or about a fifth the width of the entire region depicted in the top photograph on page 111. The central three-by-three block of squares corresponds roughly to the luminous mass of M87 shown in the top photograph on page 112.

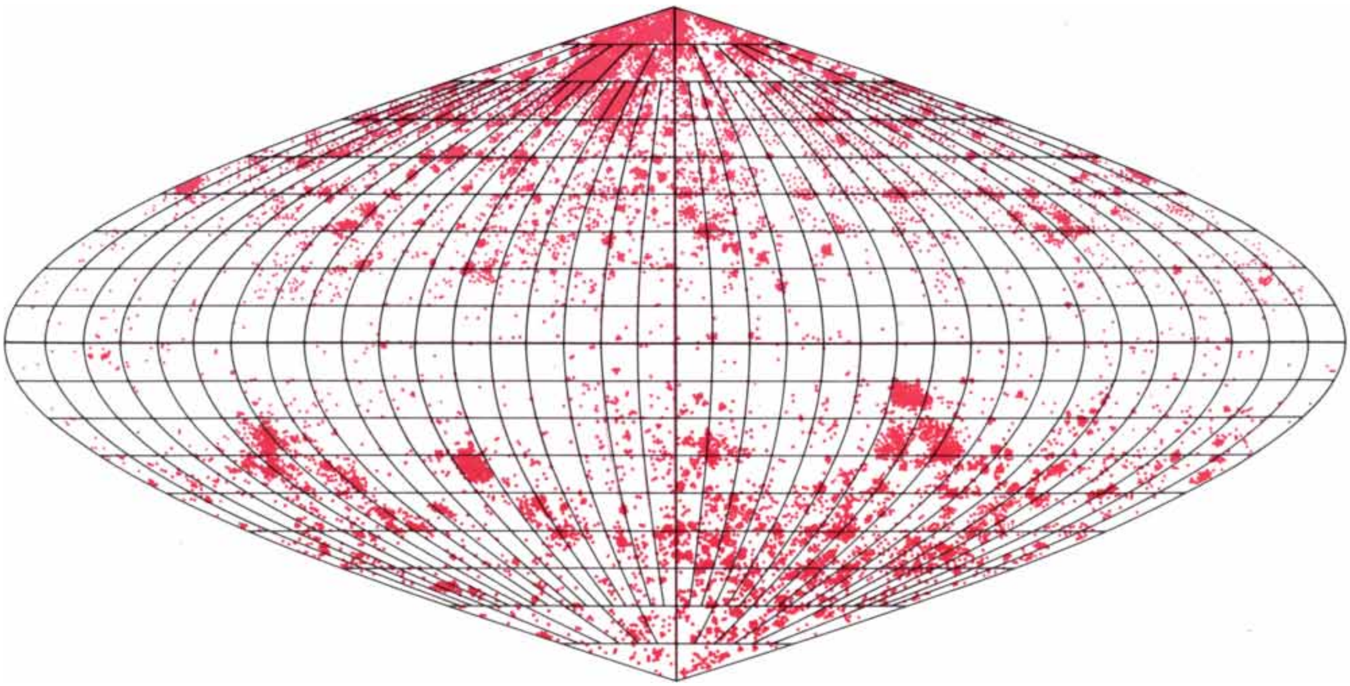
to giant elliptical galaxies such as M87 is important for cosmology in that it may provide a solution to the long-standing problem of the missing mass in clusters of galaxies. The problem originally recognized by Zwicky in his study of the great cluster in Coma Berenices is common to all large clusters. The Coma cluster, which is about 400 million light-years from our galaxy, exhibits a dense concentration of galaxies at its center. Moreover, careful study shows that in the Coma cluster, and in most similar clusters, the galaxies have swarmed together in the shape of a ball.

This shape in itself presents a problem. On the one hand, it gives the appearance of a state of equilibrium having been reached between the random motions of the galaxies and their mutual gravitational attraction. On the other hand, if one computes the total mass of all the galaxies in the cluster, one finds that it amounts to only 10 to 20 percent of the mass needed to provide gravitational stability. Hence there is a paradox. If the gravitation of the cluster were really as weak as the galaxy count seems to indicate, then the galaxies would not be concentrated in a tight ball a few million light-years across but would be spread out irregularly over tens of millions of light-years. Astronomers are reluctant to assume that new galaxies are continuously being created at the center of a cluster to maintain its observed central density or that an unknown cosmological force is at work, and so they are compelled to believe most of the mass in the cluster has still to be discovered. Where is it?

One long-standing suggestion was that the mass was hidden in the form of hot ionized gas and would be discovered as soon as X-ray observations of sufficient sensitivity were made. When the observations were finally conducted with the X-ray satellites in the early 1970's, X-ray emission was indeed discovered to be a common characteristic of rich clusters of galaxies. As in the case of M87, spectral evidence points to a hot gas as the source of the X rays. In the Coma cluster, however, the X-ray-emitting region has a diameter of some three million light-years, or more than three times the extent of the emission region of M87. The amount of mass in the hot gas was found to be comparable to the mass in the galaxies and therefore not nearly enough to bind the cluster. On the other hand, the X-ray observations do provide two additional pieces of indirect evidence that the missing mass is present. The first is that, as in the case of M87, the temperature and size of the hot gas cloud in the Coma cluster can be used to estimate the mass needed to confine it. That mass turns out to be on the order of the mass necessary to bind the cluster.

The second piece of evidence follows from the difficulty in understanding how the gas cloud came to contain the amount of iron that shows up in the X-ray emission spectrum. As far as is known, iron can be manufactured only inside a star and can enter the interstellar medium of a galaxy only when it is expelled by the explosion of a supernova. Conceivably the explosion could spew iron and other heavy elements out into the vast space between the galaxies, but such elements might also be swept out by the pressure of the "wind" created by the motion of the galaxy through the cluster or pulled out in tidal disruptions resulting from encounters between galaxies. Estimates of the efficiency of such processes, made on the basis of the conventional values for the masses of the galaxies, indicate that the hot gas cloud should contain less than a third as much iron as is observed. One can account for the discrepancy rather simply by assuming that the total mass in the form of stars is actually much larger than the conventional estimate, so that the quantity of iron supplied by the stars is correspondingly larger. An idea gaining favor is that the additional stars are distributed in massive halos of very low surface brightness around supergiant galaxies, as is the case in M87.

In 1964 Thomas A. Matthews, William W. Morgan and Maarten Schmidt of the Hale Observatories showed that a common characteristic of many rich clusters of galaxies, particularly those harboring strong radio sources, is the existence of a centrally located supergiant elliptical galaxy with an extended halo. Recently it has become evident that it is precisely those galaxies that are associated with X-ray-emitting clusters. An excellent example is the cluster A

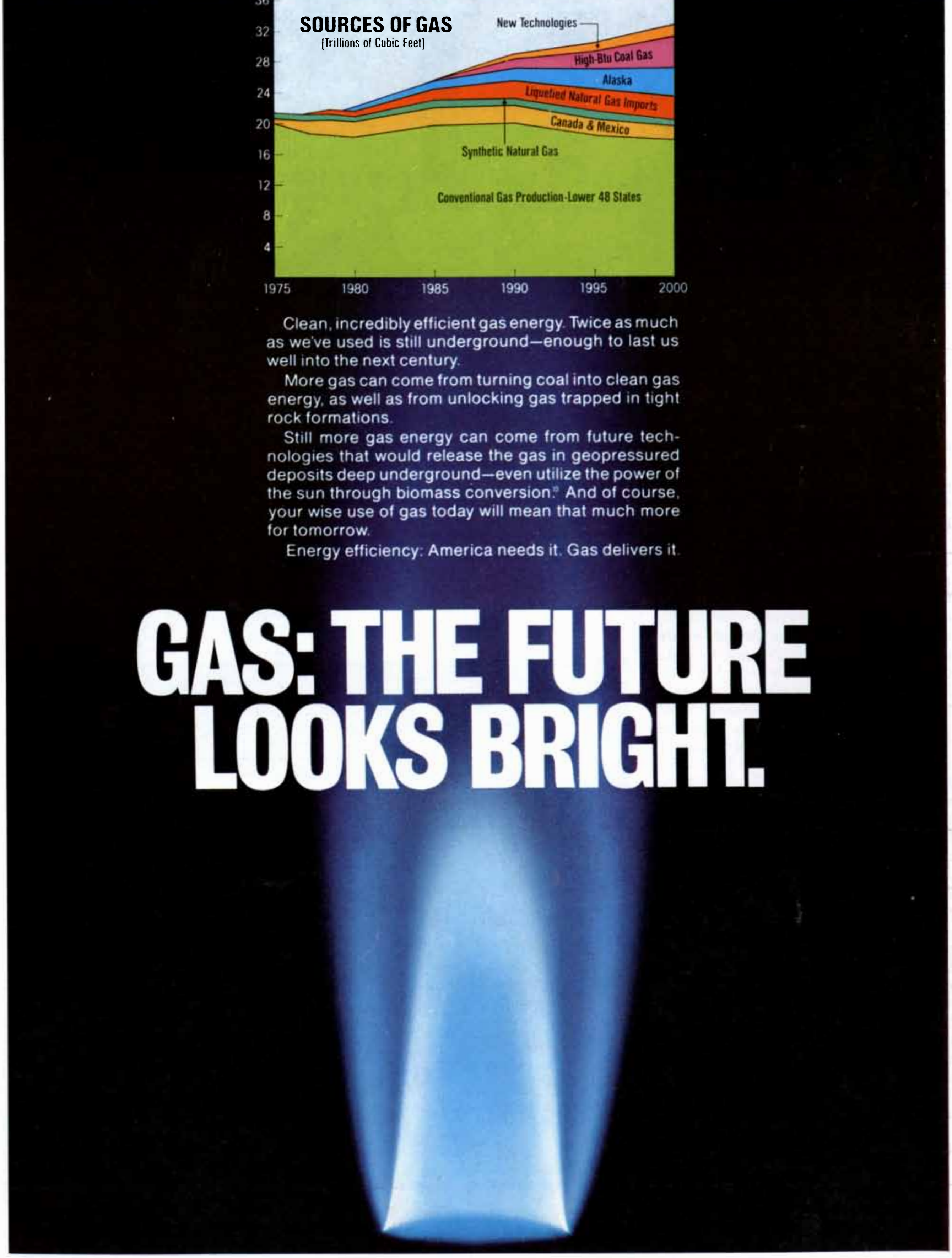


TENDENCY OF GALAXIES TO FORM CLUSTERS was already evident in the 19th century before it had been demonstrated conclusively that each galaxy is an independent star system. In 1921 C. V. L. Charlier produced this sky map by plotting 11,475 nebular objects listed in J. L. E. Dreyer's *New General Catalogue,* published in the 1890's. Here the equator corresponds to the central plane of our galaxy. Near the central plane extragalactic objects are heavily obscured by dust, making it appear that the galaxies increase in number toward the poles. Actually galaxies are assumed to be more or less uniformly distributed in all directions, except for a tendency to form clusters.

2199 (No. 2,199 in the catalogue of clusters compiled by George O. Abell of the University of California at Los Angeles). The dominant bright galaxy at the center of the cluster is NGC 6166. Astronomers classify galaxies such as NGC 6166 as cD galaxies. The *D* stands for a galaxy with a bright elliptical core surrounded by an extended envelope, which in the case of NGC 6166 has a diameter of more than two million light-years. The *c* stands for supergiant, a notation taken over from schemes for the classification of stars. NGC 6166, which encompasses a much greater volume than the Andromeda galaxy does and has several hundred times more stars, is one of the largest galaxies in the universe. The rich cluster A 2199 is a strong X-ray source, similar to the Coma cluster source. The X-ray-emitting cloud surrounds the cD galaxy, which is also a strong radio source.

The Perseus cluster of galaxies is another well-studied cluster, but it is not a well-understood one. It too harbors a centrally located supergiant elliptical galaxy, which is a strong radio source and is surrounded by an X-ray-emitting cloud and a massive halo of stars. The X-ray source is centered on the giant elliptical galaxy NGC 1275 and extends over a region with roughly the same dimensions as the halo of the stars: three million light-years. As in the case of the Coma cluster and M87, the X-ray spectrum indicates that a hot gas with a normal cosmic abundance of iron is responsible for the X-ray emission. The mass of hot gas required to explain the X-ray emission is about four times the mass of the galaxies in the cluster, and so the problem of producing the iron from the galaxies is even severer than it is in the Coma cluster. The missing mass problem is severer too. The mass required for equilibrium is about 20 times the mass that is observed in the galaxies.

The Perseus cluster includes several strong radio sources. Roughly speaking, the radio contours map out those regions of space where magnetic fields of high density coincide with large populations of high-energy electrons, a combination that results in strong nonthermal radio emission. Two of the prominent radio galaxies exhibit a head-tail shape, which suggests the interaction of the source and an intergalactic wind or, what is equivalent, the motion of the galaxies through a stationary gas. Subsequent study of head-tail sources by radio astronomers at the Westerbork radio-astronomy observatory in the Netherlands has led to the development of a model in which the swept-back contours are produced by the motion of an active radio galaxy through a hot gas at speeds of thousands of kilometers per second. The pressure in the hot gas is consistent


SOURCES OF GAS
(Trillions of Cubic Feet)
New Technologies
High-Btu Coal Gas
Alaska
Liquefied Natural Gas Imports
Canada & Mexico
Synthetic Natural Gas
Conventional Gas Production-Lower 48 States
32
28
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1975
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2000
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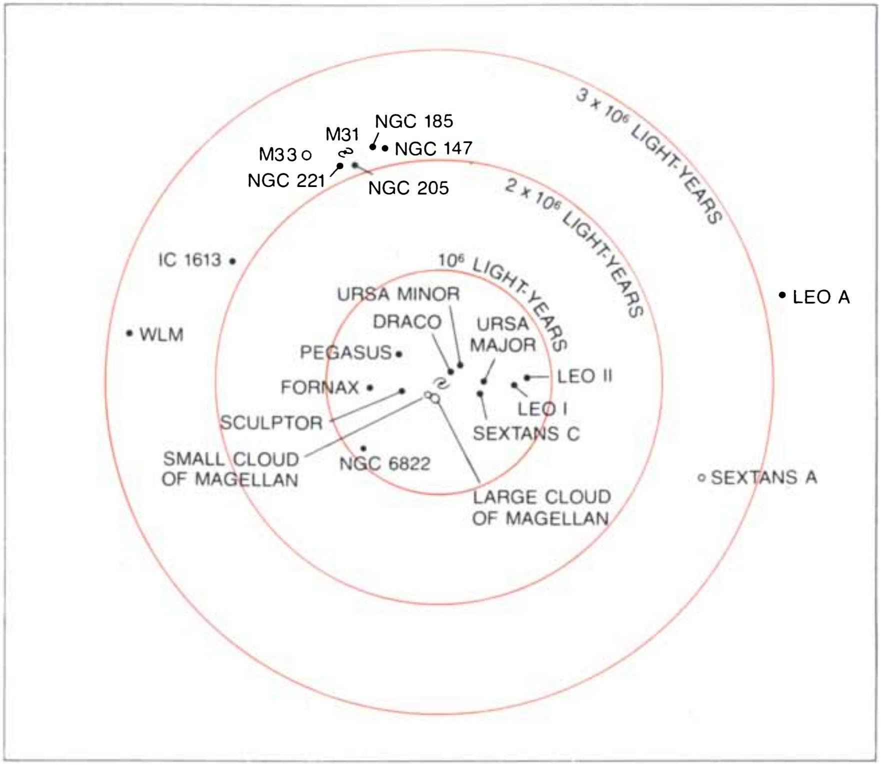
with the density and temperature required to explain the X-ray emission. As might be expected, head-tail sources are not unique to the Perseus cluster but are found in a number of other clusters, many of which have been detected as X-ray sources.

In summary, the following three facts about rich clusters of galaxies are well established. First, the mass required to keep the clusters gravitationally bound is about 10 times greater than the mass observed in the main body of the galaxies. Second, X-ray studies show that rich clusters hold a considerable amount of hot gas; the existence of the hot gas is supported by the observed head-tail structure of the radio galaxies in such clusters, and the confinement of the hot gas implies masses on the order of the amount needed to bind the clusters. Third, many rich clusters contain a centrally located supergiant galaxy surrounded by an extended halo of faint stars, and such galaxies tend to be strong radio sources.

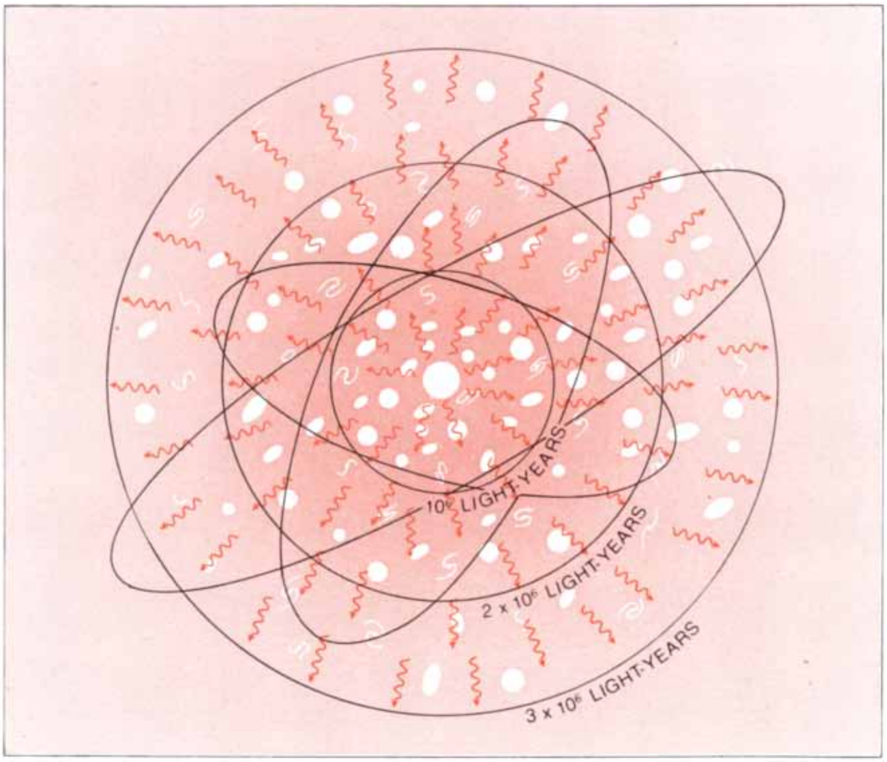
The view of a growing number of astronomers is that all the observed properties of the rich clusters are the consequence of a gravitational maelstrom. The typical rich cluster has three major components: galaxies, additional stars that form a halo around a central supergiant galaxy and hot gas. The galaxies in a cluster are in orbit around their center of mass in much the same way that the planets of the solar system are in orbit around the sun. In a rich cluster the galaxies are so large, so numerous and so densely packed that some of them inevitably encounter other galaxies. In most of the encounters the galaxies do not meet head on but are deflected only slightly as they go past each other.

The cumulative effect of these many encounters is an equipartition of energy among the galaxies; that is, galaxies moving in the same gravitational force field have the same kinetic energy, or energy of motion. The kinetic energy is proportional to the mass times the square of the velocity, and so a galaxy that is more massive than the average moves more slowly than the average. As a result of the equipartition of energy the speed of a massive galaxy is not great enough for it to maintain its original orbit, and so it spirals inward toward the cluster's center of mass. The acceleration of gravity speeds it up, but continued encounters prevent it from picking up enough speed to stabilize its orbit, and so it inexorably falls toward the center of mass.

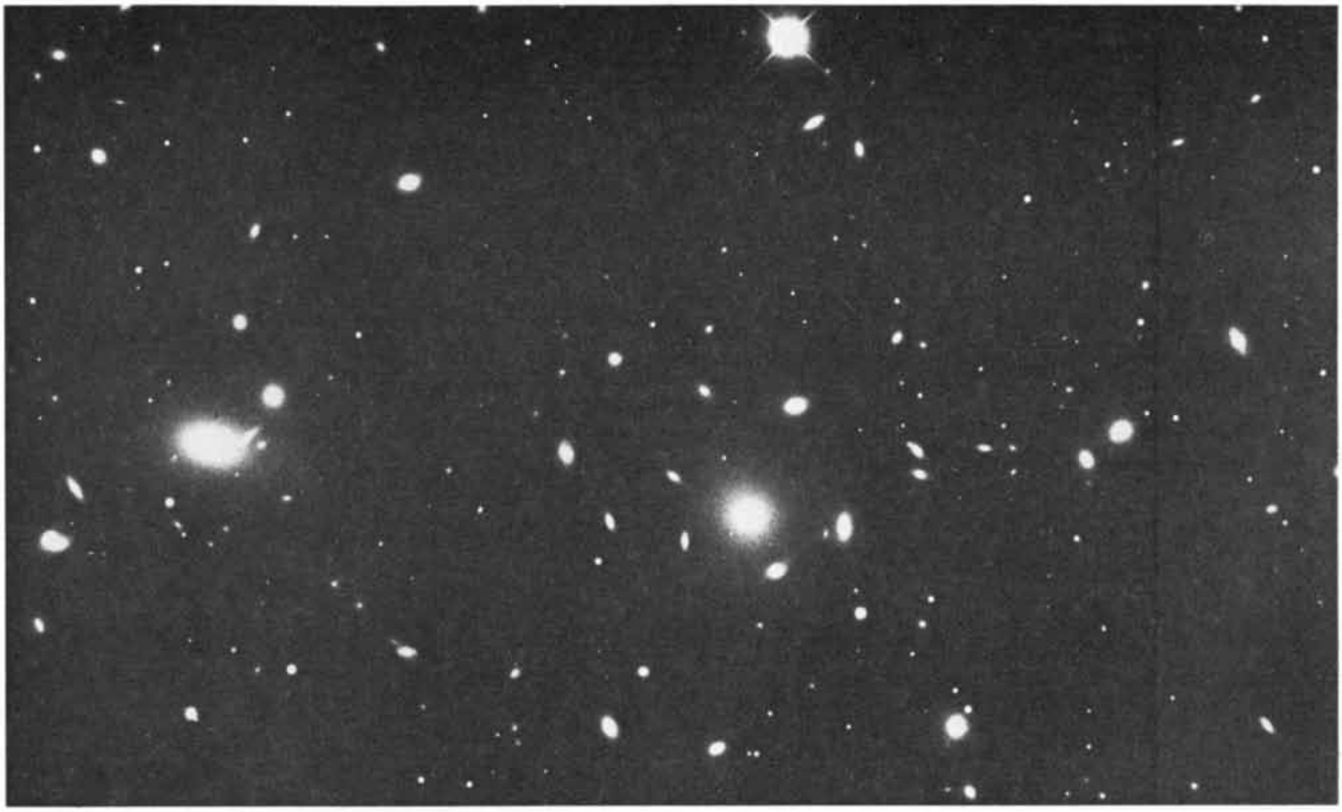
Eventually the gravitational forces that bind the stars to the infalling galaxy are overwhelmed by the combined gravity of the galaxies in the core of the cluster. Just as the ocean is pulled away from the shore at ebb tide by the moon, so are the stars pulled away from their parent galaxy. The outermost stars are



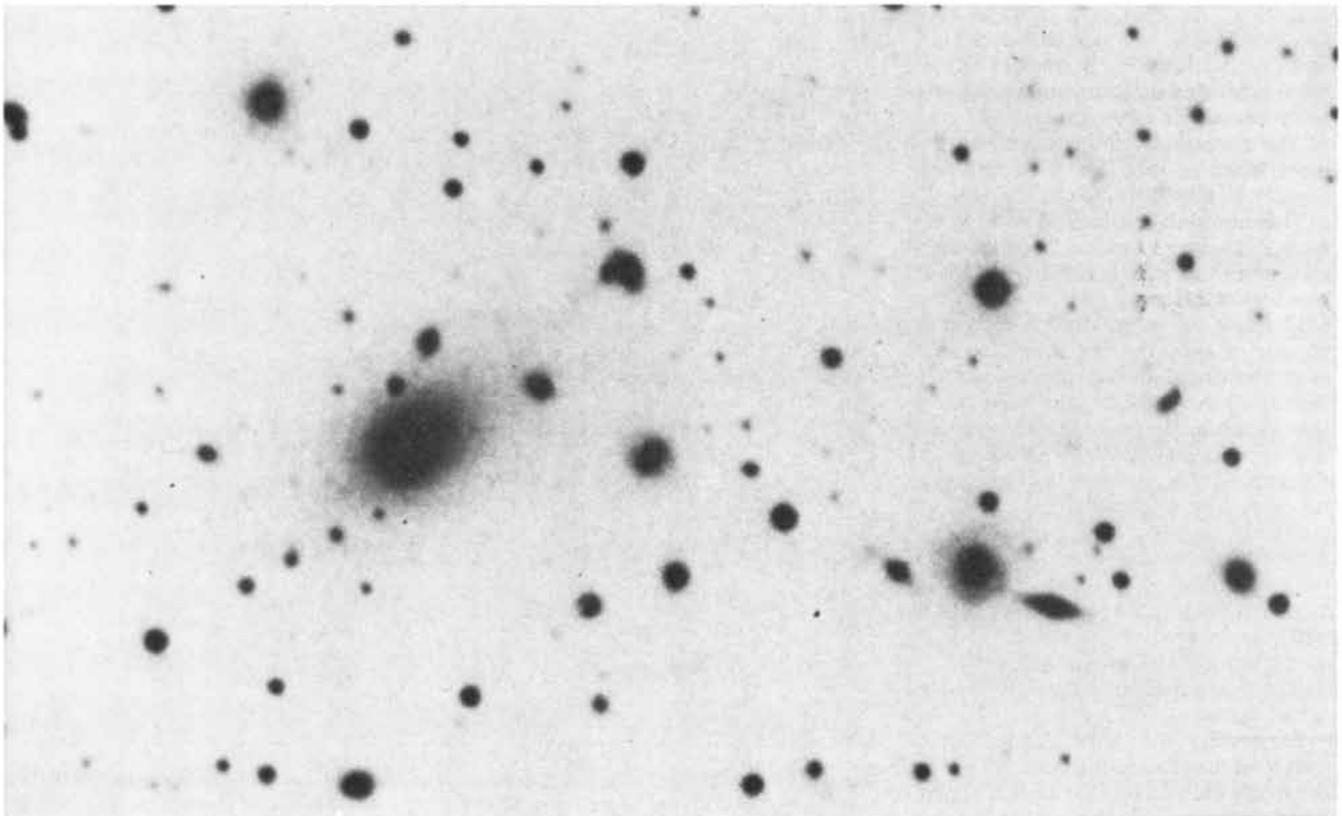
LOCAL GROUP OF GALAXIES is the one that includes our own. Consisting of some 20 galaxies of various sizes and shapes within a radius of three million light-years, the local group is typical of small clusters. About 70 percent of the mass of the group is contained within our galaxy and the Great Nebula in Andromeda, M31, two similar galaxies. This projection of the group onto a plane was made by Gerard de Vaucouleurs of the University of Texas at Austin.



RICH CLUSTER OF GALAXIES, depicted schematically, consists of more than 1,000 separate star systems that are bound together by gravity within a radius of about three million light-years. The density of galaxies increases toward the center. So does the density of hot gas (*color*), which emits X rays (*wavy lines*). In a rich cluster spiral galaxies account for only about 20 percent of the total number of galaxies; the majority of the galaxies are elliptical ones. At the very center of a rich cluster there are usually giant elliptical galaxies, or cD galaxies. A rich cluster may also contain what are called head-tail radio galaxies (*see bottom illustration on page 122*).



COMA CLUSTER, a rich cluster of galaxies in Coma Berenices, is seen in this photograph made with the four-meter telescope at the Kitt Peak National Observatory. In 1933 Fritz Zwicky presented evidence that the galaxies in this cluster were held together by their mutual gravitational attraction. The amount of mass present as visible matter, however, falls far short of the amount needed for gravitational stability. It now seems that most of the "missing mass" is in the extended halos of faint stars surrounding the large elliptical galaxies.



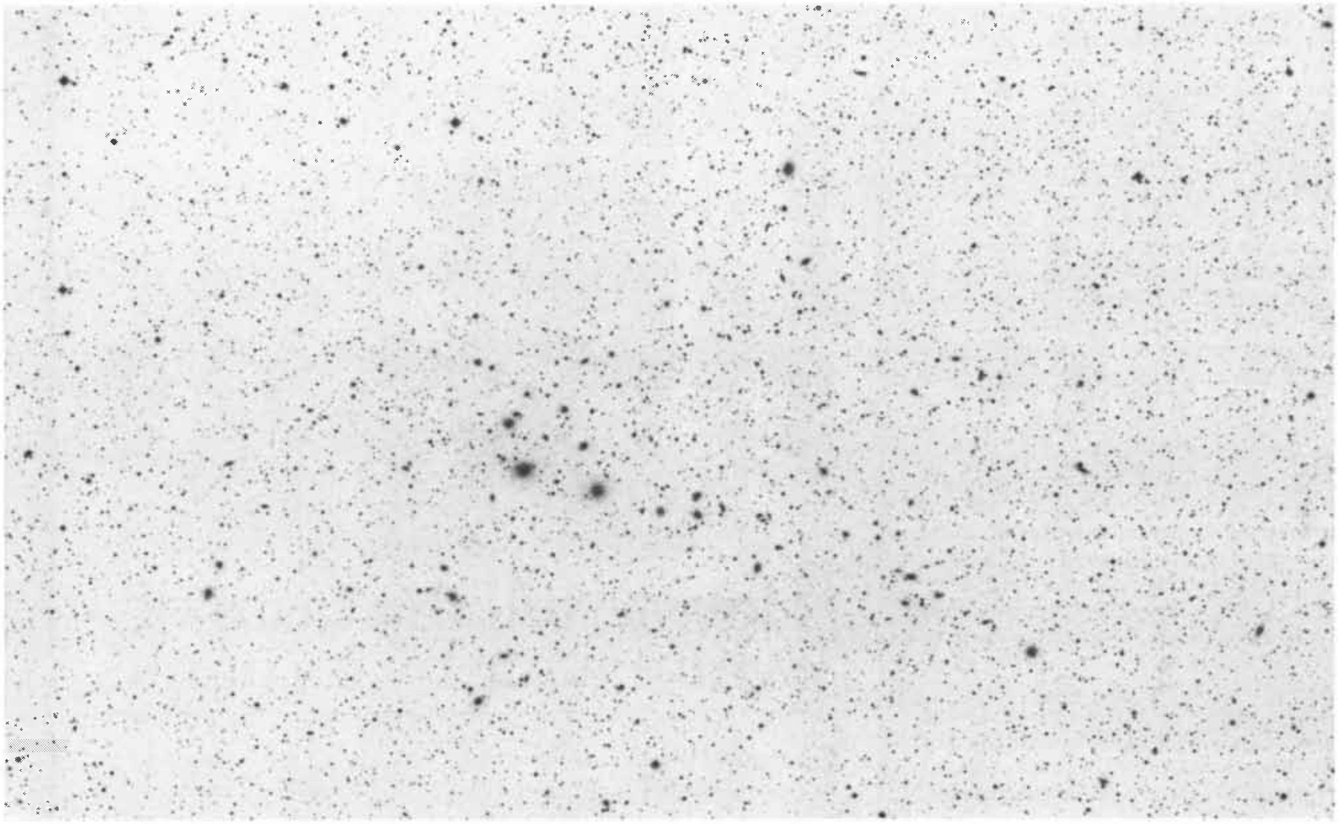
RICH CLUSTER A 2199 (No. 2,199 in the catalogue compiled by George O. Abell of the University of California at Los Angeles) has near its center the supergiant elliptical galaxy NGC 6166, the largest object in this photograph made with the 200-inch Hale telescope on Palomar Mountain. NGC 6166 contains several hundred times as many stars as either our galaxy or the Andromeda galaxy. It is one of the largest of all galaxies. Roughly 600 million light-years away, it emits strongly in both the X-ray and radio regions of the spectrum.

the first to go. Theories of the formation of galaxies indicate that the outer stars will be faint ones with a mass substantially less than that of the sun. (The heavier stars will have sunk toward the center of the galaxy through the same process that causes the galaxies to sink toward the center of the cluster.) Consequently the faint outer stars will be left behind as the galaxy descends into the maelstrom, losing more and more stars along the way. Eventually the entire galaxy will be torn apart by tides, and those stars that remain will become attached to the halo of a large galaxy at the center of the cluster.

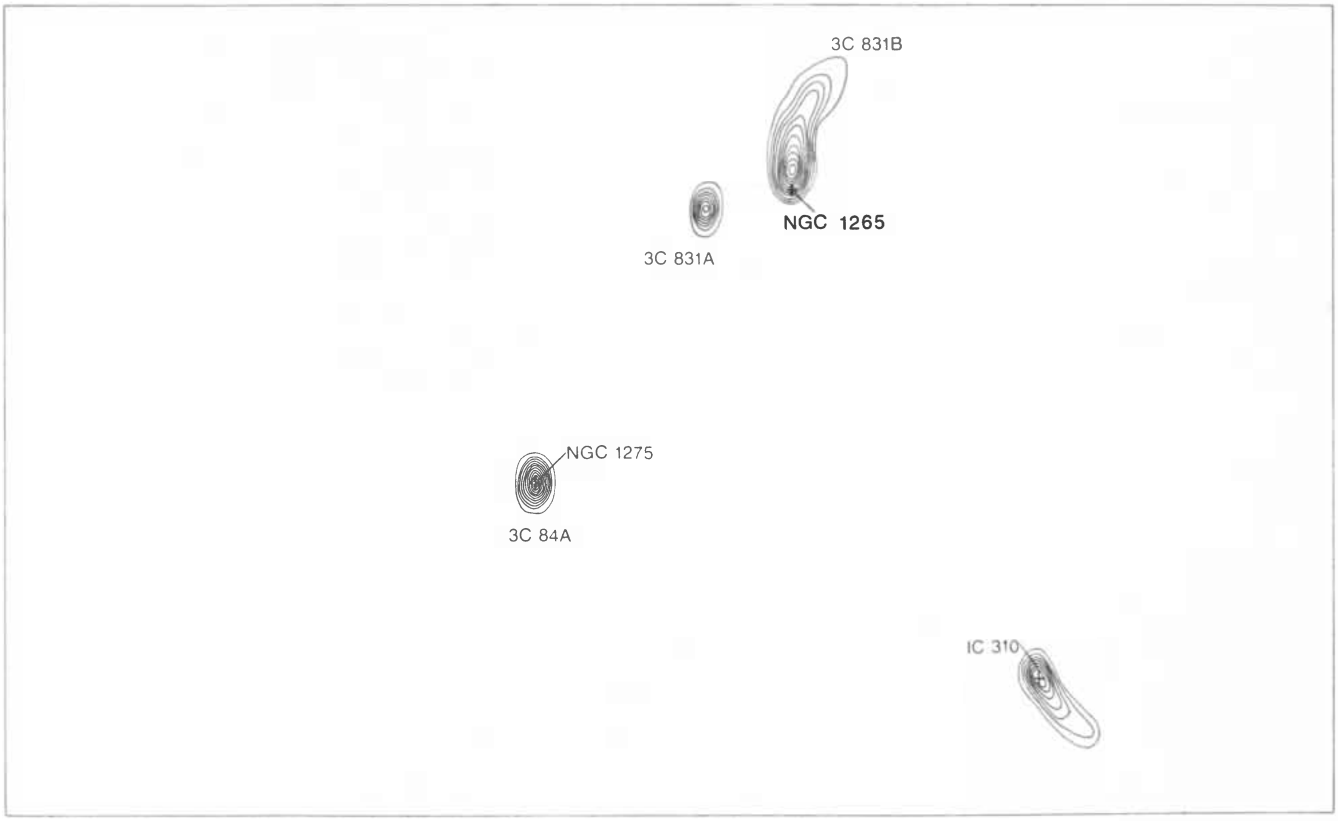
In the course of the 10 billion years of the cluster's existence a galaxy at the bottom of the gravitational potential well at the center of the cluster could have grown to a colossal size by assimilating the wreckage of a hundred other galaxies. That seems to be the most likely explanation for the extensive halo of stars around cD galaxies. The tidal stripping of stars is a gradual process, although it becomes more intense as the infalling galaxy approaches the core of the cluster. One would not expect all the wreckage to be captured in the immediate vicinity of the central cD galaxy. Some of it would be taken up by other large galaxies. By the same token one would expect the halo of the cD galaxy not to cut off abruptly but to gradually decrease in density with distance away from the core of the cluster. Recent photographic surveys of the central region of rich clusters suggest that this is the case. The halos around cD galaxies may extend out a million light-years or more to the edge of the cluster itself. The missing mass may have been found, hiding in quadrillions of low-mass stars that have been torn from galaxies, attached to the halo of the cD galaxy and spread throughout the cluster. Since they are distributed in this way, the low-mass stars are less visible than they would be if they were concentrated in the main body of the galaxies.

The association of X-ray emission with the cD galaxies would seem to be a natural consequence of the conditions in rich clusters. As a result of the high concentration of galaxies in such clusters two conditions arise that lead to the creation of an X-ray source. One condition is the injection of large amounts of gas from the galaxies into the intracluster medium. The other is the growth of the cD galaxy at the center of the cluster from the accumulation of the wreckage of other galaxies. The X-ray source is created when gas is heated by compression as it falls into the gravitational well around the cD galaxy at the center of the cluster.

Although this process is most effective at the center of clusters, it could operate on a smaller scale anywhere a large galaxy exists. An example is an



PERSEUS CLUSTER OF GALAXIES is located 17 degrees away from the central plane of our galaxy, which accounts for the large number of star images in this photograph made with the 48-inch Schmidt telescope. The cluster has a central supergiant elliptical galaxy, NGC 1275 (*see map below*), a strong radio source surrounded by a large X-ray-emitting cloud of hot gas and by a halo of stars.



STRONG RADIO SOURCES IN PERSEUS CLUSTER are identified on this map, which covers the same area as that in the photograph at the top of the page. The supergiant elliptical galaxy NGC 1275 is the most intense radio source. The radio contours of two other galaxies, NGC 1265 and IC 310, exhibit the distinctive head-tail shape, which indicates relative motion between them and the intergalactic medium. Map was made by Simon Mitton and Martin Ryle of Mullard Radio Astronomical Observatory of University of Cambridge.

irregular cluster such as the Virgo one. A galaxy that is fairly large to begin with, such as M87, will strip the stars from galaxies passing it at close range and will assimilate them into an extended halo. In the same way gas could be captured and heated as it fell into the galaxy, creating an X-ray source. The source would not be as strong as one at the center of a rich cluster because it would have a smaller reservoir of gas on which to draw.

The association of strong radio galaxies with rich clusters and supergiant galaxies would seem at first to contradict this picture. Radio galaxies show unmistakable signs of explosive activity that has thrown matter violently outward, whereas the theory of supergiant galaxies and X-ray sources involves matter falling inward. Can the two be reconciled? Can collapse lead to explosion? A growing number of astronomers think it can. There are indications that if the density of stars in the nucleus of a galaxy gets high enough, the stars will begin to coalesce and drift to the center of the galaxy, forming a supermassive object in much the same way that supergiant galaxies are thought to form at the center of clusters. The difference is that in the nucleus of galaxies the supermassive object may be a black hole, a region of space-time where the gravitational fields are so strong that matter is literally crushed out of existence. Inside a black hole stars, atoms and even nuclear particles are torn apart by enormous gravitational forces. It has been suggested that a black hole having a mass of 100 million suns may lie at the center of active galaxies. Such a black hole grows at the rate of one solar mass per year as it captures nearby matter and pulls it in.

In possible confirmation of this audacious hypothesis quite recent studies of M87, the galaxy with the jet, have shown that both the optical brightness of the galaxy and the velocity of the stars in it increase rapidly toward the center. The observations indicate that a compact object with a mass equal to that of five billion suns, possibly a black hole, is present in the core of the galaxy.

Since matter captured by a black hole cannot escape, a black hole would not seem particularly useful in accounting for an explosion. The answer to this objection may lie in the resistance that develops to the matter being crushed. As the matter swirls toward the black hole the magnetic fields accompanying it will be twisted and amplified. The resulting buildup of energy could then give rise to the observed explosive activity. Examples of a similar process occurring on a smaller scale can be found within our galaxy. There is an X-ray-emitting binary system in the constellation Cygnus known as Cyg X-1 that probably consists of a black hole of a

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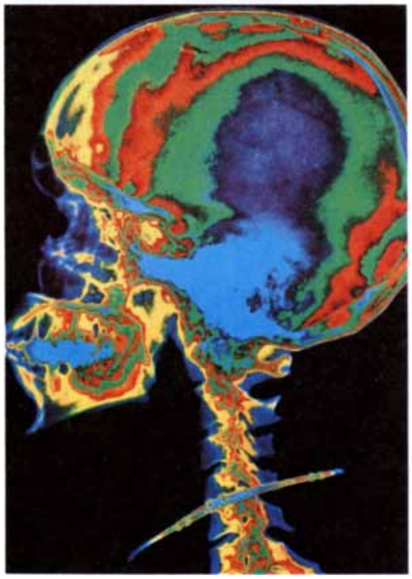

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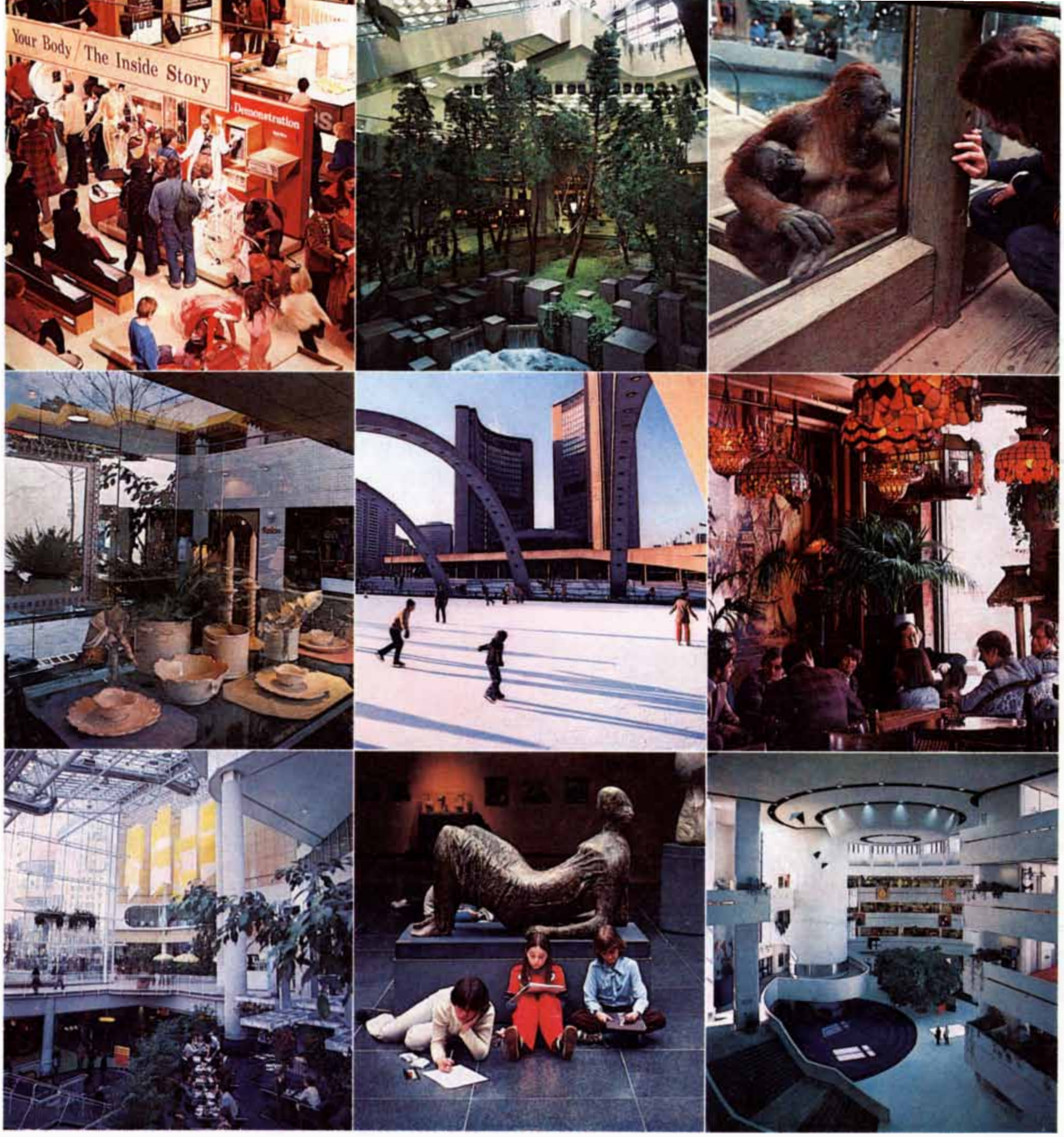

Toronto–the inside story

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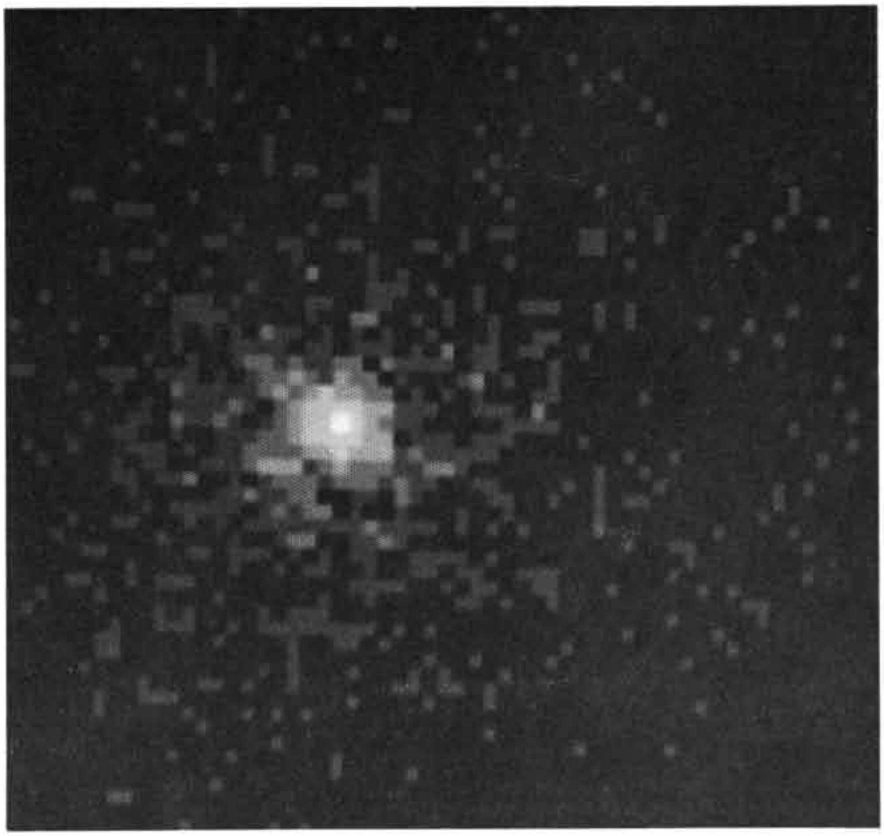
few solar masses in close orbit around a giant star. Matter flows from the outer envelope of the star into the region of intense gravitation around the black hole; gravitational energy fuels the generation of turbulent shock waves and viscous heating. The result is a rapidly fluctuating X-ray source and a variable radio source. Processes such as these operating on a galactic scale may explain the jets, double radio sources and other signs of explosive activity in active galaxies.

Now let us turn to the place of clusters in the larger scheme of things. Does the clumping hierarchy of the universe end with clusters or does it extend to yet another level, and another, and another? The case for the existence of physical associations of clusters of galaxies into superclusters is not nearly as convincing as the one for clusters, but it does seem to be improving. De Vaucouleurs has argued that the distribution and orientation of galaxies in a region of about 100 million light-years around the local group indicate the existence of a local supercluster that includes the local group, the Virgo cluster and as many as 100 other groups of galaxies. Analyses of Abell's catalogue of clusters have disclosed other statistically significant examples of superclusters with a diameter of hundreds of millions of light-years. Recently evidence for the existence of superclusters has come from X-ray observations. Investigators analyzing data from the *Uhuru* satellite have identified X-ray emission from several directions in the sky showing six or more rich clusters of galaxies. The most reasonable interpretation of their analyses appears to be that the X-ray emission is coming from a diffuse hot gas in which the clusters are embedded. The mass in the hot gas may be enough to gravitationally bind the clusters into a single system and thus provide a physical basis for the existence of this next step in the hierarchy.

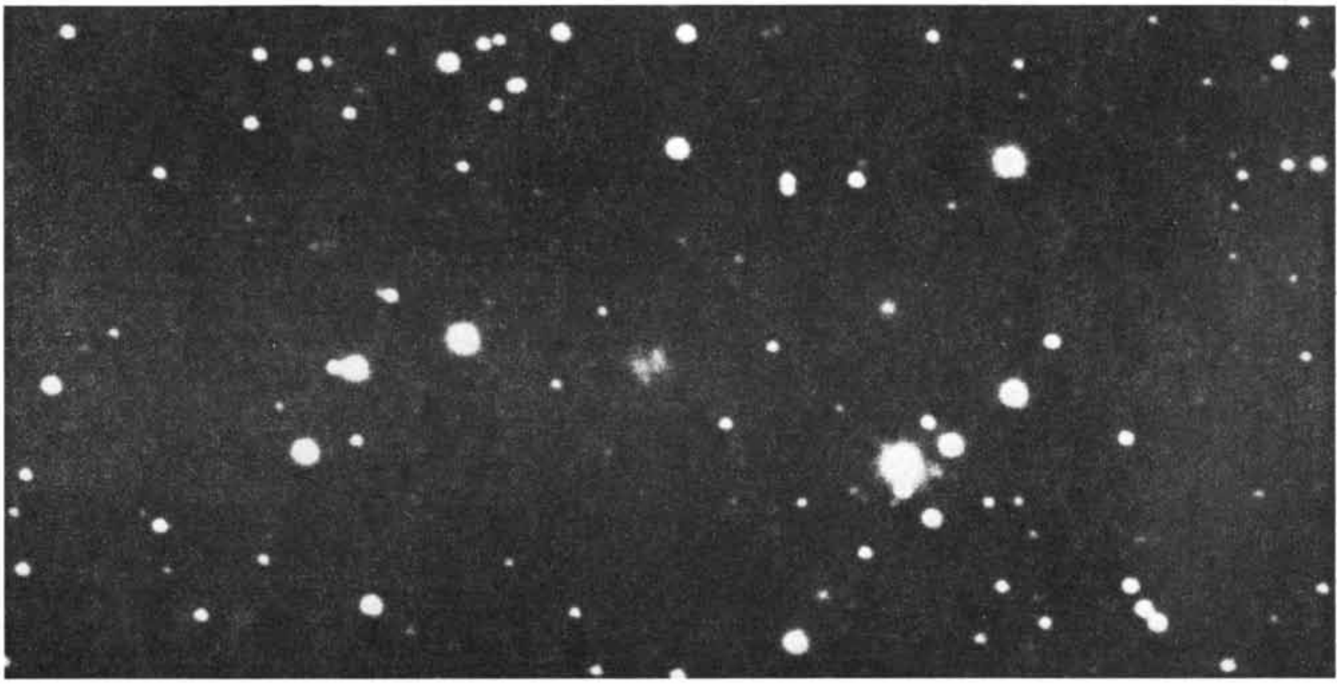
Finally we should mention the role of clusters of galaxies in determining the ultimate fate of the universe. In large measure that fate will be determined by the amount of mass the universe holds. If the mass density is larger than a certain critical value, the expansion of the universe that began with the initial "big bang" will not continue forever but will slow down, and the universe will collapse. An alternative "closed" universe is one that would go through an unending cycle of expansion, collapse and reexpansion. On the other hand, if the mass density is too low, the universe will expand forever; it will be "open." Current estimates indicate that the density of matter in the universe falls short of



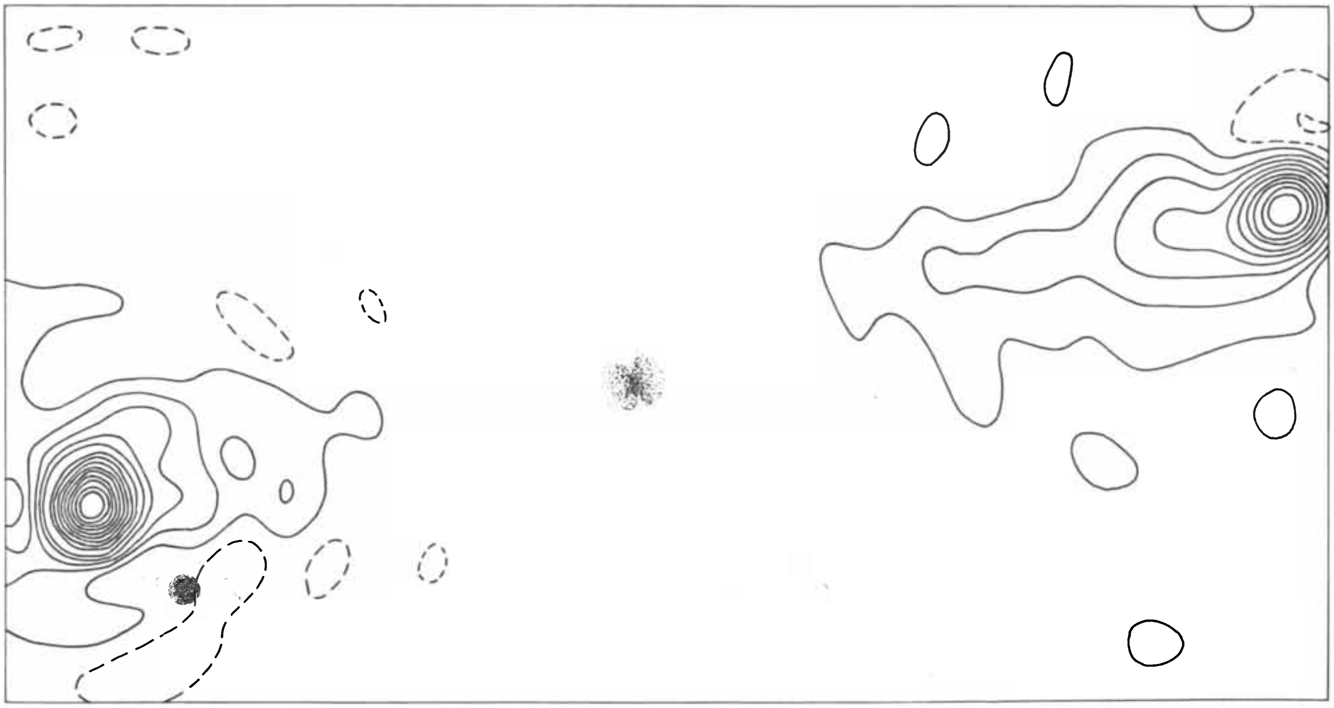
X-RAY EMISSION FROM PERSEUS CLUSTER was recorded with an X-ray telescope aboard a rocket by one of the authors (Gorenstein) and his colleagues. The region covered, which is six million light-years across, corresponds roughly to the region in the photograph and radio map on page 122. The hottest spot in the X-ray image is produced by NGC 1275.

the critical density by a factor of 10 or more, implying that the universe will indeed expand forever.

The study of clusters of galaxies may, however, have provided an important new clue to the mass of the universe. As we have seen, several lines of argument based on recent X-ray, radio and optical observations indicate that the mass of galaxies in rich clusters is about 10 times larger than had been thought. If this is true of galaxies in general, and there is growing evidence that it may be, the mass density in the universe represented by galaxies is 10 times greater than the former estimates, and the universe may be closed after all. The issue of the final state of the universe is still in doubt, but the place of clusters of galaxies in modern astronomy is not. They have proved to be one of the most important outposts from which one can venture beyond the current frontiers of high-energy astrophysics and cosmology.



MOST POWERFUL RADIO SOURCE KNOWN is a giant elliptical galaxy in the center of a rich cluster in the constellation Cygnus. The source, designated Cygnus A, is the fuzzy spot appearing just to the left of the center of this photograph made with the 200-inch Hale telescope. The galaxy's curious butterfly-shaped image was initially interpreted as being two galaxies in collision, in the belief that only some such cataclysm could account for the object's intense radio output. It is now thought the bifurcation in the image is caused by dust, which may indeed obscure much of the entire galaxy because the object is not as bright as many of the neighboring elliptical galaxies.



RADIO MAP OF CYGNUS A reveals that the radio emission is concentrated in two lobes extending some 500,000 light-years on each side of the galaxy. The contours in the radio map suggest that electrically charged matter has been violently ejected from the galaxy and is moving outward at high velocity. Cygnus A is also a source of X rays. The radio map was made at the Mullard Radio Observatory.

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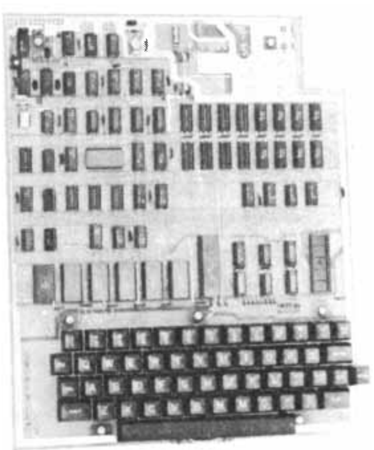

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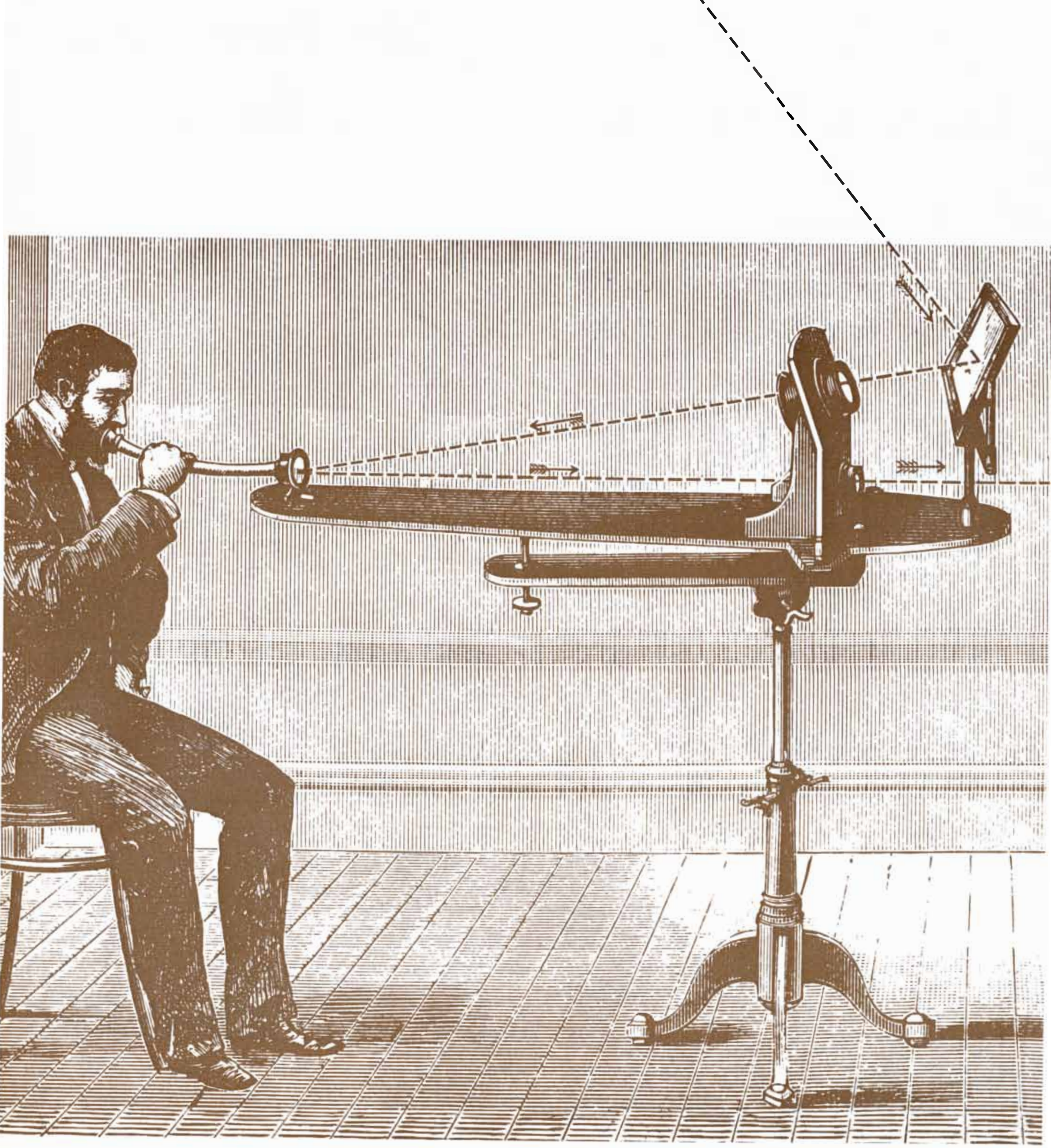

In Bell's "Photophone," sunlight was bounced from a reflector through a lens to a mechanism that vibrated in response to speech. This caused the light beam to vary in intensity. At the receiving end, a selenium detector translated these variations into electrical current to recreate speech through a telephone receiver.

77 years before we invented the laser, Professor Bell had a perfect application for it.

In 1880, only four years after he invented the telephone, Alexander Graham Bell received a patent for a remarkable idea—using light, rather than wire, to carry phone calls.

Professor Bell built an experimental "Photophone" that transmitted his voice over a beam of sunlight. It didn't work very well, however.

Sunbeams are scattered by air, rain and fog. In any event, the sun doesn't always shine. The Photophone, unfortunately, was an idea whose time had not yet come.

A new kind of light

By the 1950's, scientists again were looking for a way to use light for communications.

In September, 1957, Charles Townes, a Bell Labs consultant, and Bell Labs scientist Arthur Schawlow conceived a way of producing a new kind of light—extremely intense, highly directional, and capable of carrying immense amounts of information.

Townes and Schawlow received a basic patent on their invention—the laser.

Since then, Bell Labs scientists have invented hundreds of lasers, including many firsts—gas and solid-state lasers capable of continuous operation, high-power carbon dioxide lasers, liquid dye lasers that produce pulses shorter than a trillionth of a second, and tiny semiconductor lasers that work reliably at normal temperatures. Some of these, no larger than grains of salt, may emit light continuously for 100 years.

Getting the light to the end of the tunnel

While we were developing lasers to generate light, we also looked for a way of shielding it and guiding it for long distances and around curves.

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Spin-off

Laser light is now used in many other ways—to perform delicate eye surgery, detect air pollution, read product codes at supermarket checkouts, and do a variety of manufacturing tasks. Western Electric, the Bell System's manufacturing and supply unit, was the first company to put the laser to industrial use back in 1965. Hundreds of applications in many industries have followed.

Sometimes, it takes a lot of work and a long time to make a bright idea—like Professor Bell's—a reality. Often, the things we invent, such as the laser, benefit not only Bell System customers, but society in general.

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The Mechanisms of Abrasive Machining

Much machining is done not by cutting but by abrasion. How the abrasive grains do their work is investigated so as to improve the efficiency of the abrasion process

by Leonard E. Samuels

It is seldom possible to make a finished metal part, particularly for a machine consisting of many parts, simply by casting it or forging it. The part usually needs further finishing by one of the processes that come under the broad heading of machining. One might suppose that finishing of this kind would be done by means of sophisticated cutting tools, and indeed much of it is. Much of it is done, however, by the brute-force techniques of grinding and polishing, which can be described as abrasive machining.

One advantage of abrasive machining is that it can work with metals that are too hard or too tough to be machined with single-point tools. The common abrasives are much harder than the hardest metal. Alumina (aluminum oxide), silicon carbide and diamond, which are the most widely used abrasives, are among the hardest substances known. Another advantage of abrasive machining is that it is better than most other machining processes at producing parts with superior dimensional accuracy and good surface finish. The process is also quite flexible: abrasives can be employed in a variety of ways for different objectives.

As a result of its advantages machining with abrasives is a major industrial process. Grinding and polishing machines constitute about a fourth of the dollar value of the machine tools sold annually in the U.S. The process has therefore been much studied from the engineering point of view. Rarely, however, has what might be called the physics of it been examined. By this I mean studies that examine the interaction of the individual abrasive particles and the surface of the workpiece (the part being machined), that consider the abrasive particles as individual cutting tools and that enable their effects to be summed so that a sound mathematical analysis of the process can be developed. This is the kind of work my colleagues and I in the Materials Research Laboratories of the Australian Department of Defence have been doing. In particular I should like to acknowledge the contribution of my late colleague Thomas Mulhearn, who was responsible for the basic concepts of our approach.

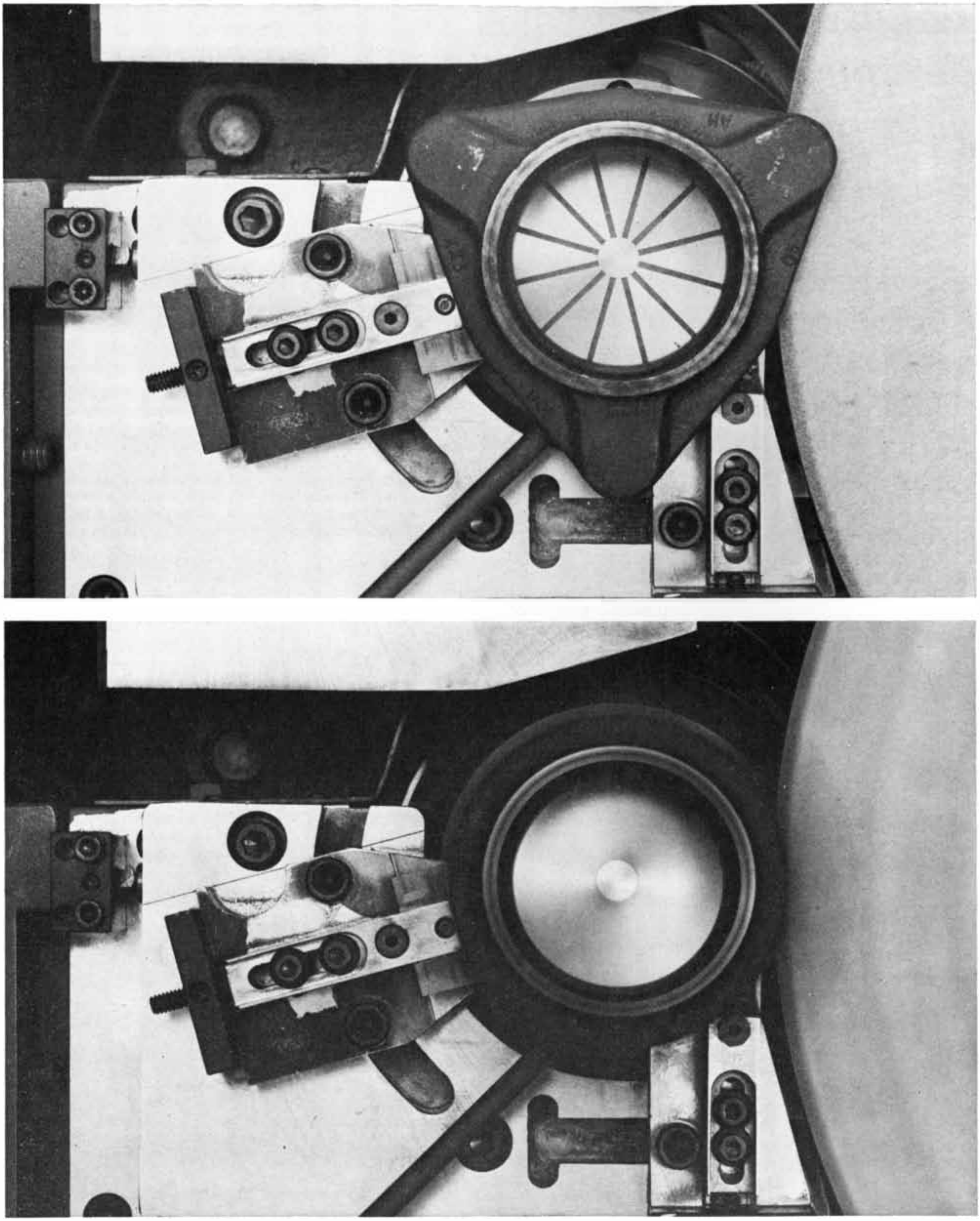
One might wonder what the need is for such studies, apart from scientific curiosity. Most straightforward machining processes can be analyzed satisfactorily by assuming that the volume of material swept out in the workpiece by the tool is removed from the workpiece. This might be called 100 percent efficiency of removal of material. The swept volume can be calculated simply enough, even for a complex machining process such as grinding. Much indirect evidence suggests, however, that the efficiency of abrasive machining is a great deal less than 100 percent, in which event the calculations are of limited value unless the efficiency can be determined at least approximately. Moreover, it would clearly be helpful to know what factors control the efficiency of material removal so that they could be optimized in a rational way.

Other important practical problems that need to be considered are that the abrasive points wear rapidly and that the surface of the workpiece undergoes much more heating in abrasive machining than in conventional machining, so that the effect on the part when it is in service can be unfavorable. Abrasive machining cannot be improved in any of these respects (except by trial and error) until the processes that occur when an abrasive particle sweeps across a metal surface are understood.

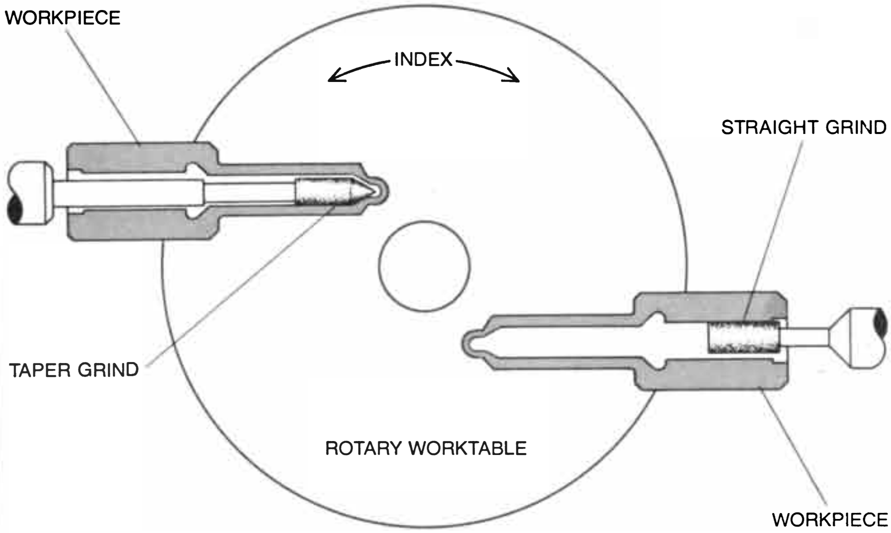
The trouble is that the process is extremely complex, primarily because of the irregular shape of abrasive particles. Only a small portion of such a particle actually cuts into the metal. The shape of that portion is all that really matters, the dimensions and shape of the rest of the particle being almost immaterial. Certainly the bulk of the particle is necessary to transmit forces to the active point, just as a lathe tool must have not only a cutting point but also a shank by which it can be gripped. Moreover, a new active point might form in the bulk material if the original point broke off in service. The diameter of the particle limits the number of particles that can be packed into a given volume, and hence the diameter has an effect on the number of active points that can touch a given area of the workpiece. These are secondary matters, however, and one can safely concentrate first only on the shape of the point that will be interacting with the workpiece.

Since the shape of an active point is most irregular, the first step in developing a model of the action of the point is to choose a simple shape to represent the point. The simplified shape must be both adequately realistic and simple enough to make it possible to analyze the process. A sphere is perhaps the simplest first choice and has been adopted by some investigators.

My colleagues and I think, however, that a sphere is not sufficiently realistic to be acceptable as a model. Various experiments suggest that spherical points would not remove material by producing ribbonlike chips, whereas all forms of abrasive machining undoubtedly remove chips of this type in profusion. A simple experiment demonstrates what I mean. Prepare a well-polished surface of a soft metal and place it against paper coated with an array of small glass spheres. Apply a normal force between the two and move the specimen laterally. Separate the paper and the metal workpiece carefully and examine the ends of the grooves that have been made in the surface of the metal. A bulge of metal (called a prow) will be found to have formed ahead of each groove. No groove will be found to terminate in a machining chip. A model



WORK AREA of a grinding machine (*top*) shows the abrasive wheel at the right, grinding a workpiece, in this case a ball-bearing spindle hub for three makes of automobile manufactured by the General Motors Corporation. The abrasive wheel is made of aluminum oxide. The metal surface with spokelike lines is a magnetic fixture that holds and rotates the workpiece, and the metal structures that abut the workpiece on the left and the bottom right hold the part in place. The dark tube that rises from the bottom left supplies a coolant liquid during grinding. In the bottom photograph the grinding wheel and the workpiece are in motion in a simulated grinding operation. (In a real grinding operation the work area would be covered by safety guards that would conceal the wheel and the workpiece.) The coolant was withheld for the sake of photographic clarity. This machine is an external grinder made by the Bryant Grinder Corporation for the New Departure–Hyatt Bearings Division of the General Motors Corporation. A loading arm and clamp have been retracted for clarity.



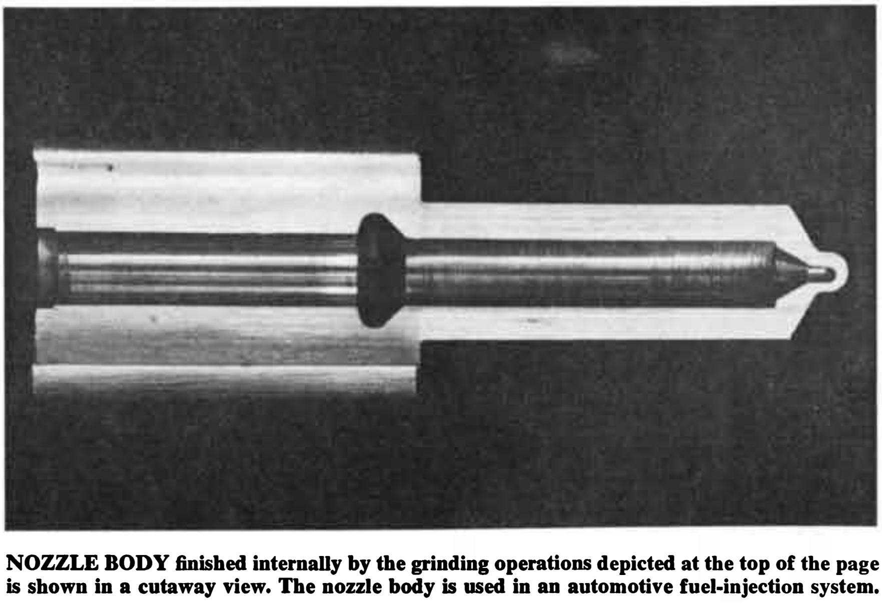
GRINDING OPERATION involving work on the inside of a nozzle body is depicted schematically. The machine works on two parts simultaneously. In one operation (*right*) a straight grinding wheel finishes a cylindrical bore that has been made in the workpiece. In the other operation (*left*) a conical grinding wheel extends through the bore and grinds a tapered seat for a nozzle valve. Both grinding wheels are then withdrawn and the rotary worktable is turned 180 degrees, so that the finished part (the one at the right) is brought around for removal and the part still needing to have a cylindrical bore ground is positioned for grinding. A loader arm picks up the finished part and positions an unground one on the left side of the worktable.

that does not incorporate this fundamental feature of abrasive machining (the production of chips) seems to us to be of little value.

The next-simplest possibility is to represent the abrasive point by a pyramid. This is the model my colleagues and I have been exploring, starting with the simplest case, in which the pyramid moves in a direction perpendicular to one of its faces. Two facts define the pyramid. The first one is the peak angle, projected in the direction of motion. (It is the angle a face of the pyramid makes with a vertical line through the peak of the pyramid.) Together with the depth and length of cut this angle determines the volume swept out in the workpiece when the point traverses it.

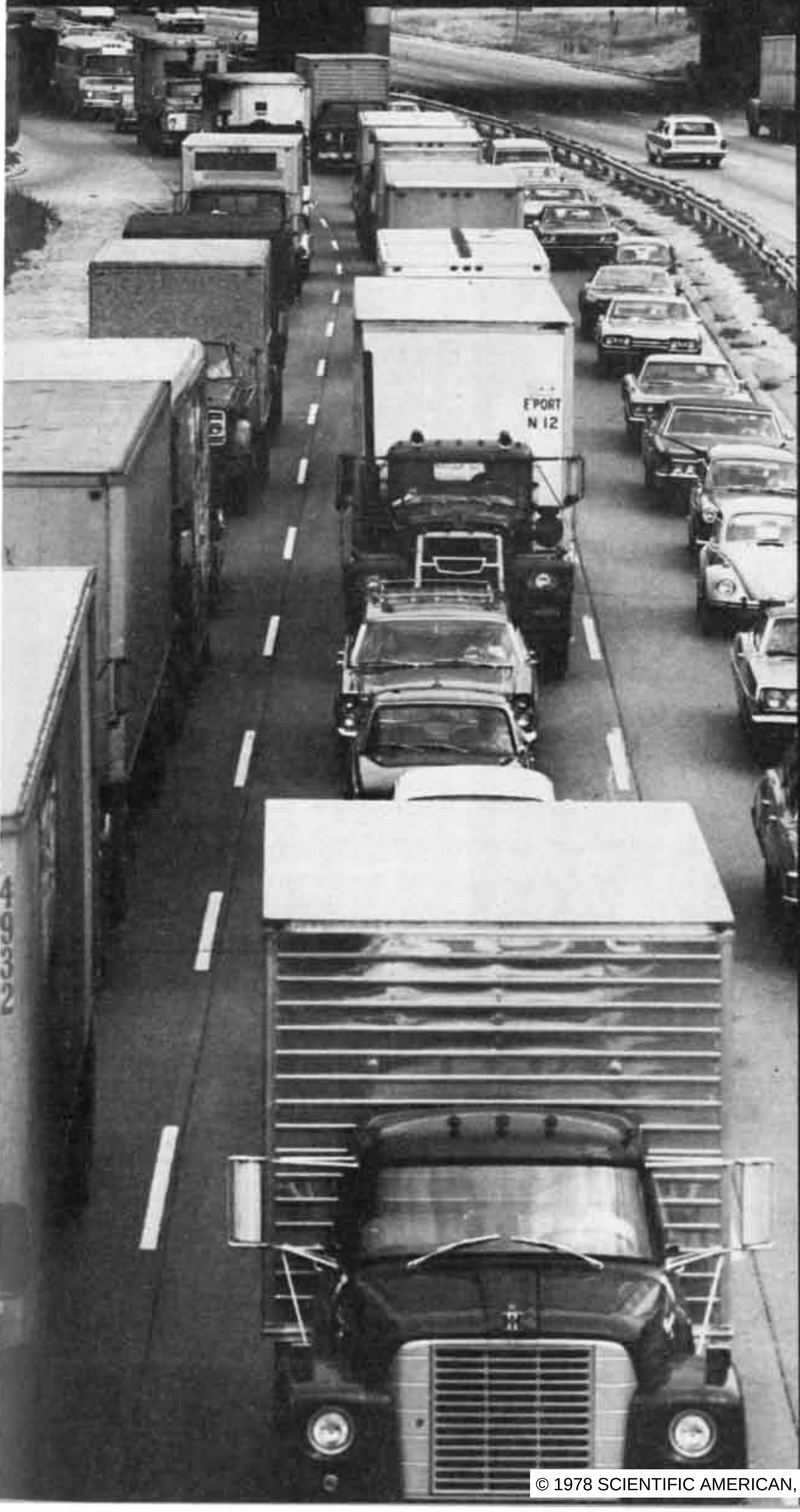
The second fact is the angle of inclination between the advancing face of the pyramid and the surface of the workpiece. This angle determines whether the volume swept out in the surface of the workpiece is actually removed. In other words, it is a fundamental factor in the efficiency with which the abrasive removes material from the workpiece.

The pyramid is analogous to a simple *V*-point tool employed in an ordinary machining operation such as planing. The angle of inclination of the working face can therefore be described



NOZZLE BODY finished internally by the grinding operations depicted at the top of the page is shown in a cutaway view. The nozzle body is used in an automotive fuel-injection system.

Myth:
Truck traffic can move only on the highways.



Fact:
More than two million truckloads moved by railway last year.

Piggybacking—the movement of truck trailers or containers by rail—is the fastest-growing part of the railroad business. It set a new record in 1977 and it's now our second-largest source of traffic—next to coal.

The piggyback concept has come of age. Better yet, it has generated a wealth of innovations and improvements. Containerized cargo destined for foreign countries now moves across America by rail. New designs in flatcars are saving fuel and increasing loads. Truck trailers that actually ride either roads or rails with two separate sets of wheels are being tested.

This is good news for the railroads, but it's better news for the consumer and the nation. Many piggyback trains move their cargo with about half the fuel that would be required by trucks to move the same goods.

Usually there's a cost saving in piggyback shipments, too, with the advantage of fast, long-distance travel and expedited door-to-door delivery service.

Because these truckloads travel on the railroads, not the highways, the motoring public enjoys a greater degree of safety and less congestion, while damage to the highway system is reduced.

Not all trucks can move by train, but thousands more are doing so every year. And the ones that do aren't leaving potholes in your favorite road.

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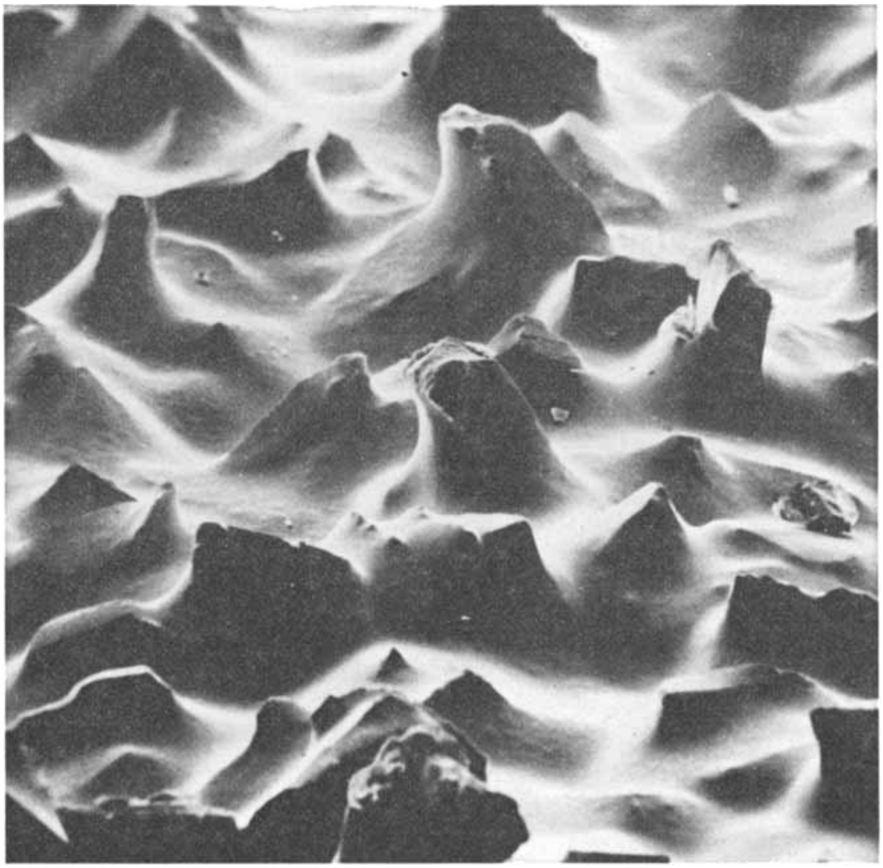
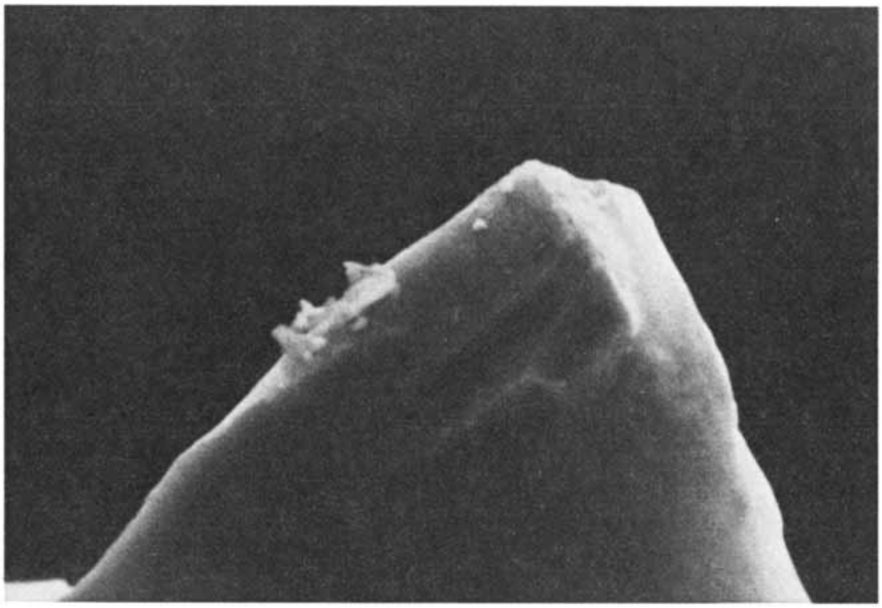


ABRASIVE PAPER was photographed in silhouette in the scanning electron microscope. The paper had a coating of silicon carbide abrasive particles, which appear at an enlargement of 300 diameters. In an abrasive operation relatively few of the particles would be in contact with the surface of the workpiece at any time, and only the tip of such a particle would be involved.



ABRASIVE PARTICLE of silicon carbide appears at an enlargement of 250 diameters in this scanning electron micrograph. The author and his colleagues study abrasion by cementing such a particle to a disk, operating the one-particle disk as though it were a grinding wheel and examining the fragments of metal thrown off from the surface of a workpiece. In such an operation the rake angle of the particle is crucial. If one imagines a workpiece being moved from left to right against this particle, the rake angle lies between the left-hand face of the peak and a vertical line through the peak. Many long, ribbonlike chips are removed when the rake angle is more positive than a critical value for a given metal, whereas only a few small blobs of metal (termed "prows") are removed when the rake angle is more negative than the critical value.

by terms that are standard in machining practice: the clearance angle (the amount by which the rear face of the pyramid is raised from the surface of the workpiece) and the rake angle (the angle between the advancing face of the pyramid and a vertical line). The clearance angle is not of fundamental significance provided that it is more than zero degrees. The rake angle, however, is of great significance. Note that in the standard convention it can be either positive or negative [*see illustration on page 138*].

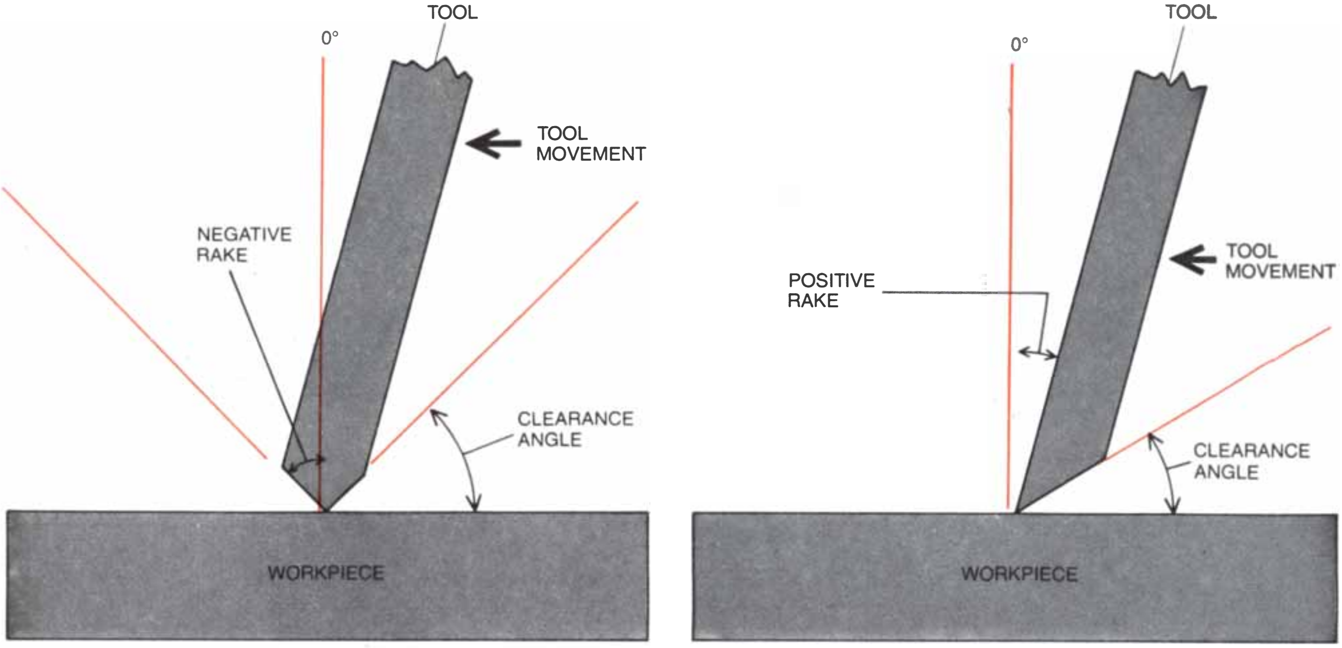
An experiment simulating a pyramidal abrasive point can be done with a *V*-point tool. Set up a pyramidal point made of a hard material (much harder than the workpiece but not so hard that it will break easily) so that it can be indented into the surface of the workpiece by a controlled amount and so that the rake angle can be varied. Then move the point across the workpiece for a certain distance with a known rake angle. Retract the point and examine the groove that has been produced. Repeat the experiment for a range of rake angles.

Grooves produced by pyramids that have positive rake angles always terminate with a long, ribbonlike chip. One can assume for the moment that all the volume of workpiece material swept out by the point is now in this chip and that all the material (that is, the entire volume of the groove) would be removed from the workpiece if the chip broke off. The chip is certain to break off when the tool reaches the edge of the workpiece; it will probably break off much sooner. As a first approximation, then, the efficiency of removal of material is 100 percent. One can say that the point is operating in a cutting mode.

Grooves that have been produced by pyramidal points with sufficiently negative rake angles terminate in a prow. Ridges form at each side of the groove, so that the size of the prow is constant no matter how far the point has moved. The volume of material swept out in the workpiece by the point is now in the prow and the ridges. The point is operating in a plowing mode, and the efficiency of removal of material is zero unless the prow or the ridges break off.

In the cutting mode material moves continuously upward past the rake face of the tool, separating a ribbon of material from the surface. In the plowing mode material first moves upward in advance of the rake face and then moves around the face into the side ridges, resembling the bow wave formed in front of a ship. The important point is that material is merely moved on the surface but is not detached. It can be removed only through some secondary process: the prow fractures or is pushed off an edge of the workpiece or the side ridges break off. All these things happen in practice, but the efficiency of removal of material is at best low.

The transition from the cutting mode



NEGATIVE AND POSITIVE RAKE ANGLES are depicted for single-point cutting tools, which are in principle much like single abrasive particles. If the workpiece were made of steel, the critical rake angle, that is, the angle that is the dividing line between efficient and inefficient removal of material, would be zero degrees. A cutting point or an abrasive point with a rake angle more positive than a critical value will cut a chip, whereas a point with a rake angle more negative than the critical value will merely plow a groove. The critical rake angle for a given metal can be changed by heat that develops on the surface of the workpiece and by liquids employed as coolants.

to the plowing one in these simulation experiments occurs over a fairly narrow range of rake angles for most metals. One can therefore define a critical rake angle for each metal and can assume that points with rake angles more positive than the critical value cut a chip, whereas points with rake angles more negative than the critical value merely plow a groove.

The reality of this model can be tested first with what is perhaps the simplest abrasive-machining process, in which a workpiece is moved in one direction across the surface of abrasive paper. Such paper is made by cementing a thin layer of abrasive particles on a paper backing, the particles usually being deposited in such a way that their long axis is roughly perpendicular to the plane of the paper. As a result the workpiece is likely to be in contact with a sharp point on most particles. It will become evident that this is a favorable situation.

One can now carry out with real abrasive paper the type of experiment described above for simulated paper with spherical particles. The chips and prows produced in the workpiece by points with a range of rake angles are remarkably similar to the ones produced by the model *V*-point tool. Evidently a model that represents an abrasive point by a pyramid has a degree of realism.

The implication then is that the efficiency of removal of material in an abrasive-machining process will be determined by the proportion of abrasive points in contact with the workpiece that have a rake angle suitable for cutting a chip. One can test this implication by again employing the simple process of unidirectional abrasion on coated abrasive paper. First it is necessary to estimate the rake angles of the abrasive points that will be in contact with the surface of the workpiece. One way to do this is to photograph the abrasive paper in silhouette in a scanning electron microscope and to measure on the photograph the angle of inclination of the faces of points that seem likely to be in contact with the workpiece.

By making many such measurements one can prepare a distribution curve for the rake angles of the active abrasive points. This curve is a basic characteristic of the particular abrasive device. For a paper coated with 220-mesh silicon carbide abrasive, and with steel as the workpiece material, about 25 percent of the points have a rake angle more positive than zero degrees (the critical rake angle for steel, as determined in a simulation experiment with *V*-point tools). Hence about 25 percent of the points can be expected to operate in a cutting mode; the rest will plow. The efficiency of removal of material should therefore be about 25 percent.

These estimates can be supported by examining a number of groove terminations produced in the experiments described above and estimating how many have a chip attached to them. The agreement between the two estimates is always good. Moreover, these principles can be developed into a mathematical model of the abrasion process. Predictions based on the model agree well with measurements of abrasion rates obtained in fully practical abrasion operations.

The general conclusion is that the efficiency of an abrasion device is determined by the proportion of chip-cutting abrasive points. One could improve the efficiency by using an abrasive that has a higher number of acute points. Abrasive points fracture easily in service, however, and the more acute they are the more readily they fracture. Therefore one resorts to a compromise shape that gives optimum performance. It is possible to improve the abrasion efficiency by tilting all the abrasive particles in one direction, but the gain of efficiency in that direction would be matched by a reduction in the other one.

Another important factor in the efficiency of abrasion is the value of the critical rake angle. The more negative the angle, the larger the proportion of the points in an abrasive paper that will cut a chip. The value of the critical angle is a characteristic of the workpiece material, but at present it is not possible to say categorically what basic properties of the material determine the value of the critical angle. Most probably it is determined chiefly by friction phenomena between the chip and the rake face of the abrasive point. Friction, however, is such a complicated matter in machining

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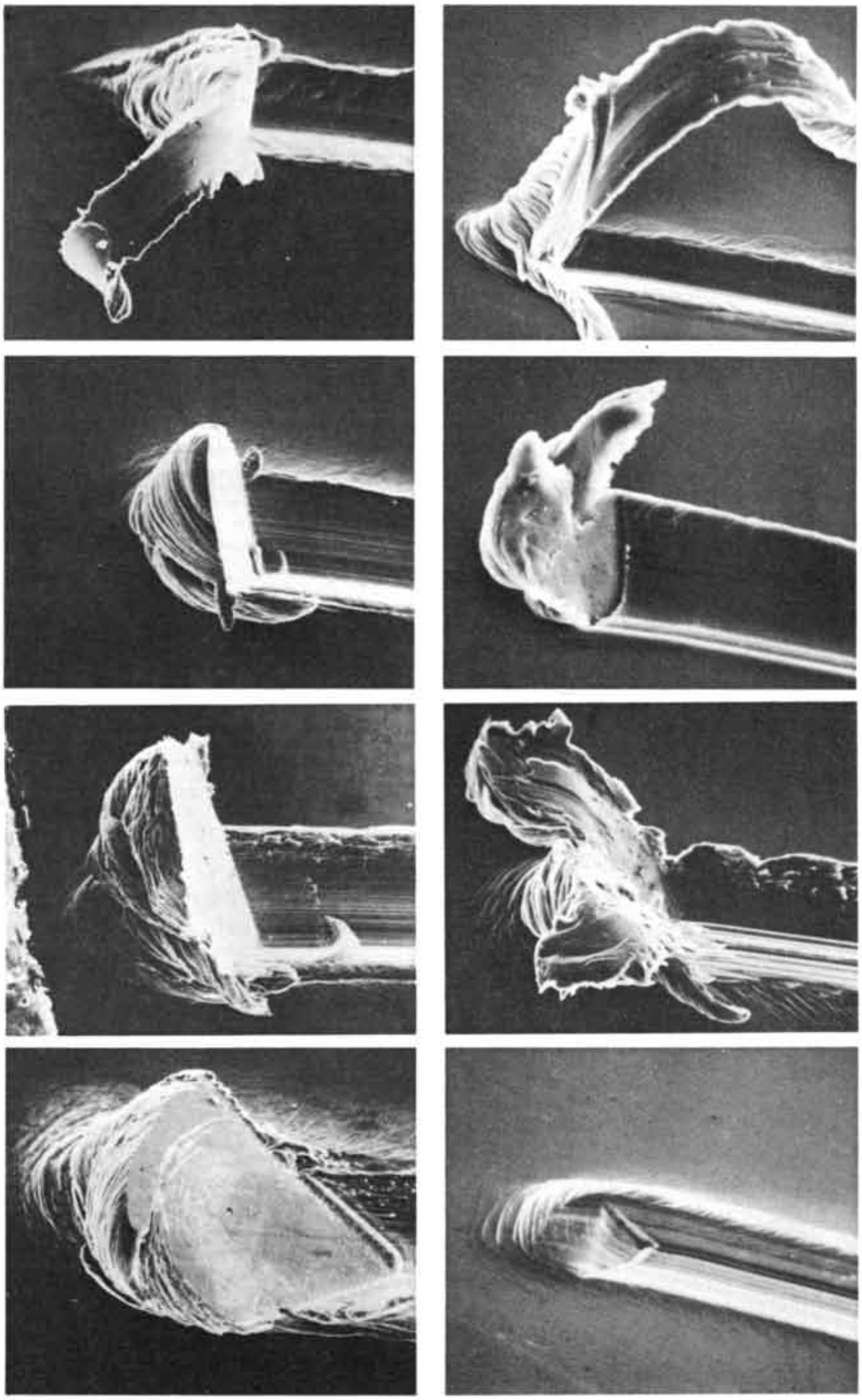
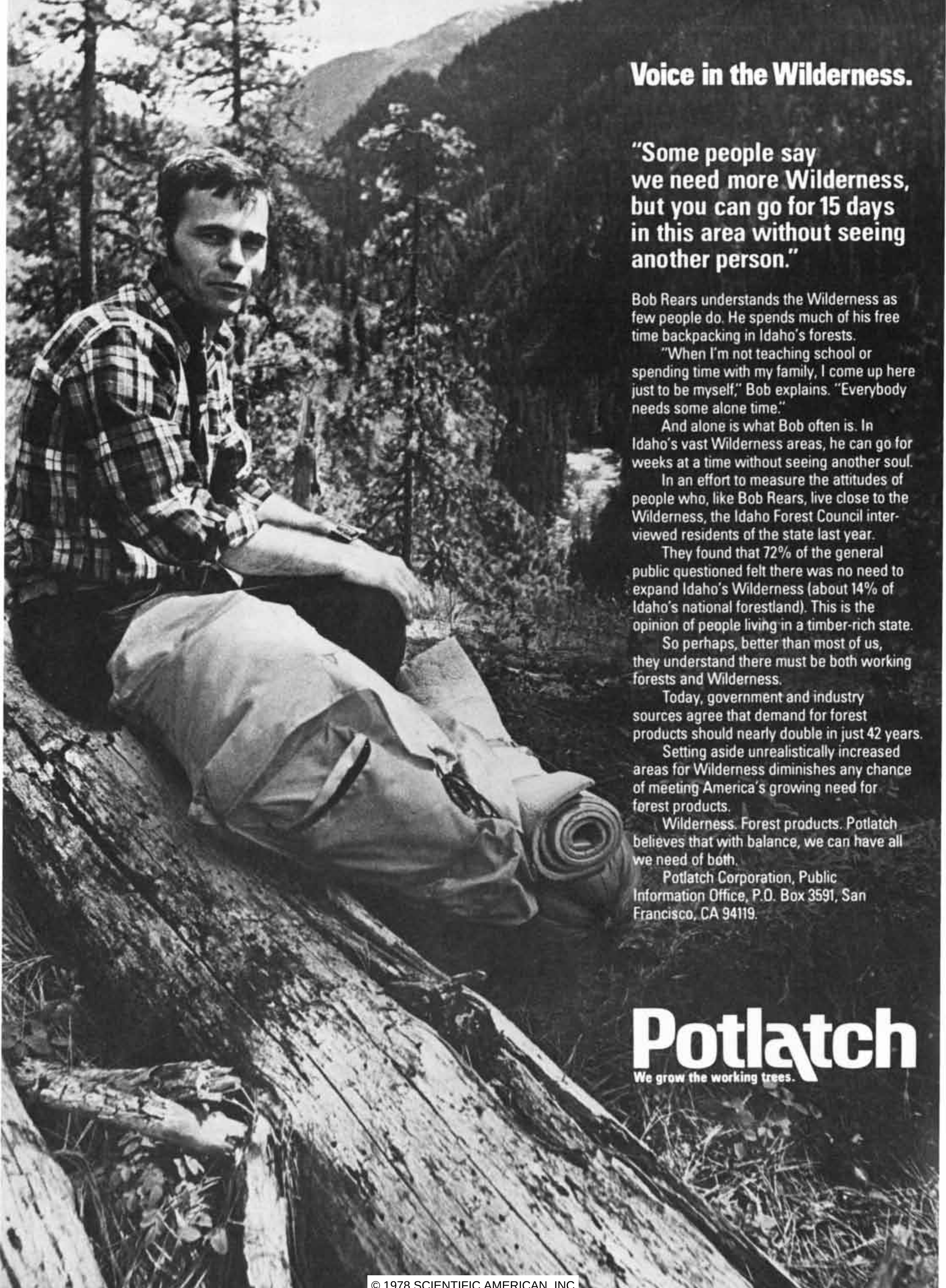
that it cannot at present be analyzed even for the simplest case of a normal machining tool. Nevertheless, the implication is that the efficiency with which material is removed can be expected to vary with different metals in a way that cannot be related directly to any one of a particular metal's simple physical properties.

The hypothesis that frictional effects are involved is supported by the critical rake angle's being affected by the presence of an effective lubricant. Liquids are frequently used in abrasive-machin-



MACHINED PARTICLES in aluminum appear in these micrographs. In the four micrographs at the left the aluminum was machined with a *V*-point tool at rake angles of 20, 0, −20 and −60 degrees, reading from the top. Tools with rake angles more positive than zero degrees cut a chip; tools with negative rake angles plow a groove. The photographs at the right show the termination of grooves produced in aluminum with abrasion by silicon carbide paper. The rake angle of each particle can be judged approximately by its imprint at the end of the groove. The chips and prows formed are quite similar to the ones produced by the model *V*-point tools. The enlargement of the micrographs at the left is 125 diameters; of those at the right, 500.


Voice in the Wilderness.
"Some people say we need more Wilderness, but you can go for 15 days in this area without seeing another person."
Bob Rears understands the Wilderness as few people do. He spends much of his free time backpacking in Idaho's forests.
"When I'm not teaching school or spending time with my family, I come up here just to be myself," Bob explains. "Everybody needs some alone time."
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In an effort to measure the attitudes of people who, like Bob Rears, live close to the Wilderness, the Idaho Forest Council interviewed residents of the state last year.
They found that 72% of the general public questioned felt there was no need to expand Idaho's Wilderness (about 14% of Idaho's national forestland). This is the opinion of people living in a timber-rich state.
So perhaps, better than most of us, they understand there must be both working forests and Wilderness.
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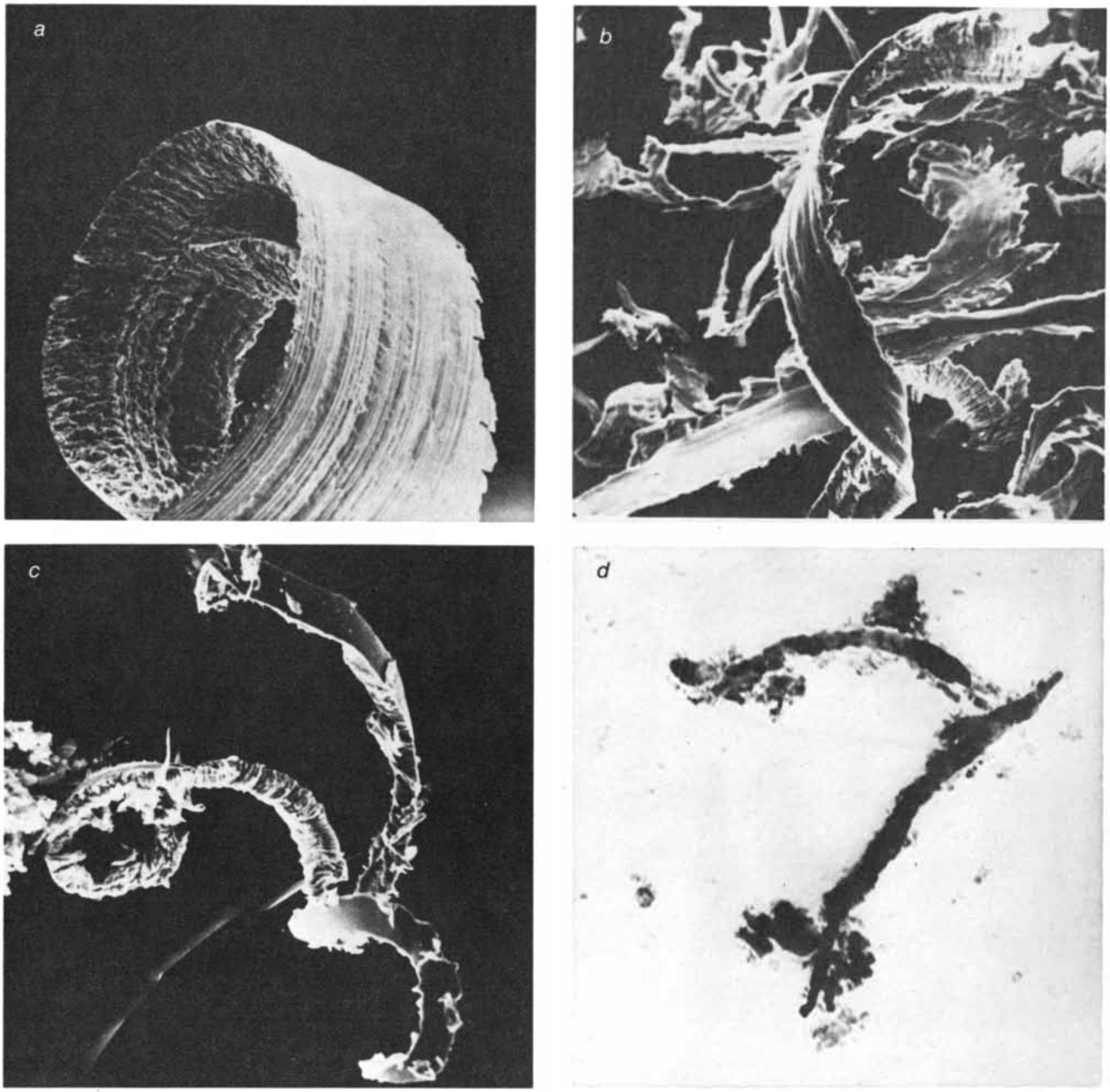
ing systems and are often referred to as lubricants. In many instances their main role is as a coolant, but nonetheless some of them appear to perform a genuine lubricating function.

Carbon tetrachloride is an example of a good genuine lubricant, at least at low cutting speeds. Although it can be used (with care) in laboratory experiments, it is too toxic to be employed in industry. Among other things, it makes the critical rake angle more negative. For example, it changes the critical angle for steel from zero degrees to −20 degrees. Although this effect has been explored only in a preliminary way, it may represent a means of exploring the effectiveness of the lubricants employed in industrial abrasive machining, where lubrication is at present largely a black art.

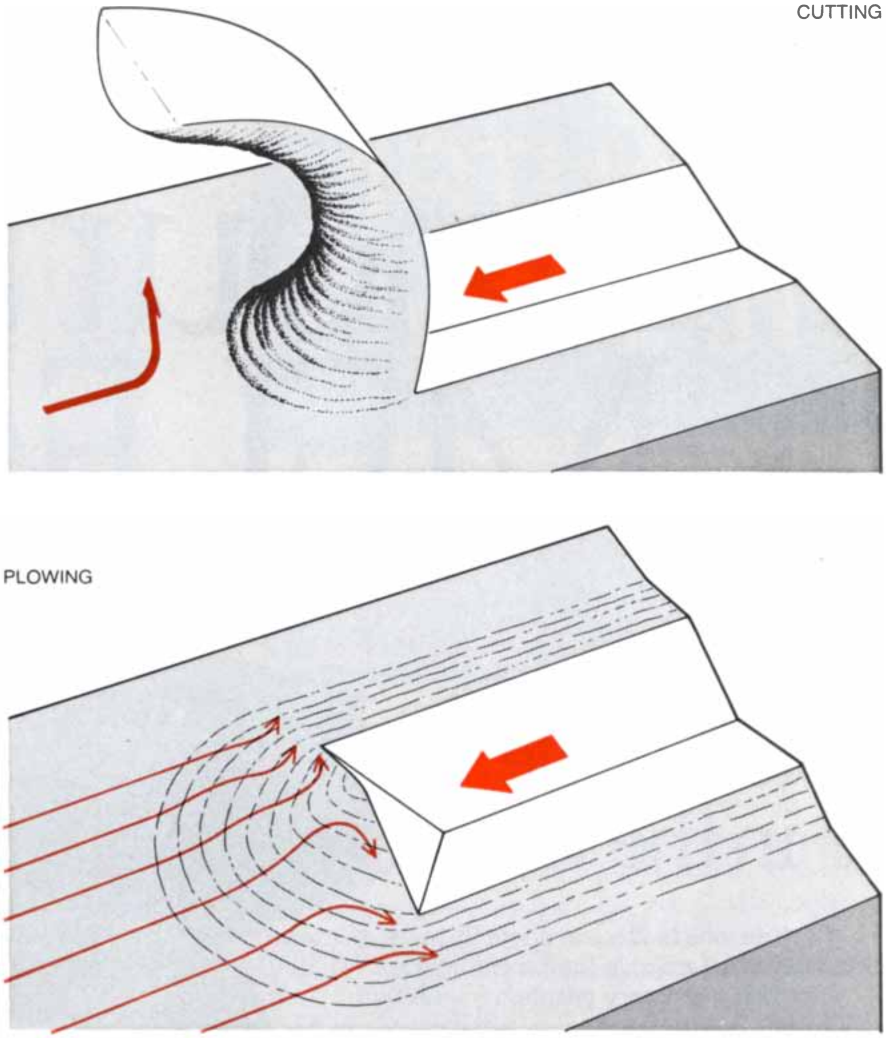
The critical angle for steel (but not for other common metals) is also affected by the temperature of the surface layers of the workpiece. For example, the critical angle of steel is improved to −40 degrees when a temperature of 450 degrees Celsius is exceeded. Such a temperature could easily be reached in the surface layers of a steel workpiece in industrial grinding.

It is probable also that the critical angle for most metals is affected by the shape of the abrasive point as it is projected in a plane perpendicular to the direction of motion. For example, the critical rake angle for brass is about −40 degrees for a *V*-point tool; a point with a rectangular shape has the less favorable value of −10 degrees. The shape of real points is somewhere between the *V* point and the rectangle.

So much for simple abrasion proces-



ABRADED MATERIAL indicates by its shape the mechanism by which the material was removed. A chip (*a*) produced by turning steel on a lathe is ribbonlike and curved. One surface of the ribbon is fairly smooth, perhaps showing longitudinal score marks; it is the face that rubbed against the rake face of the tool. The other surface shows regularly spaced serrations. The particles removed when steel is ground (*b*) or abraded (*c*) have the same characteristics but are smaller and more irregular. The particles removed when copper is polished (*d*) are even smaller, but they are undoubtedly ribbons and seem to have the periodic structure typical of a machining chip. Evidently grinding, abrasion and polishing are all similar abrasive-machining processes. Enlargements are respectively 90, 520, 472 and 70,800 diameters.



CUTTING AND PLOWING are portrayed for a *V*-point tool. In cutting (*top*) a ribbon of material is separated from the surface of the workpiece. The material moves upward past the rake face of the tool continuously. In plowing (*bottom*) the material first moves upward ahead of the rake face and then moves around it and into side ridges. Cutting is an efficient method of removing material; if any material is removed in plowing, the process is highly inefficient.

ses. The real practical interest lies in grinding and specifically in the grinding of steel. The basic characteristic of a grinding operation is that a disk or wheel composed of abrasive particles bonded together is rotated at high speed. The workpiece is moved past a surface of the disk, usually the cylindrical surface. The abrasive points typically make contact with the workpiece at a speed of about 30 meters per second (67 miles per hour). The depth of interaction of an abrasive point and the workpiece is small, amounting to a few micrometers. The points merely flick the surface of the workpiece.

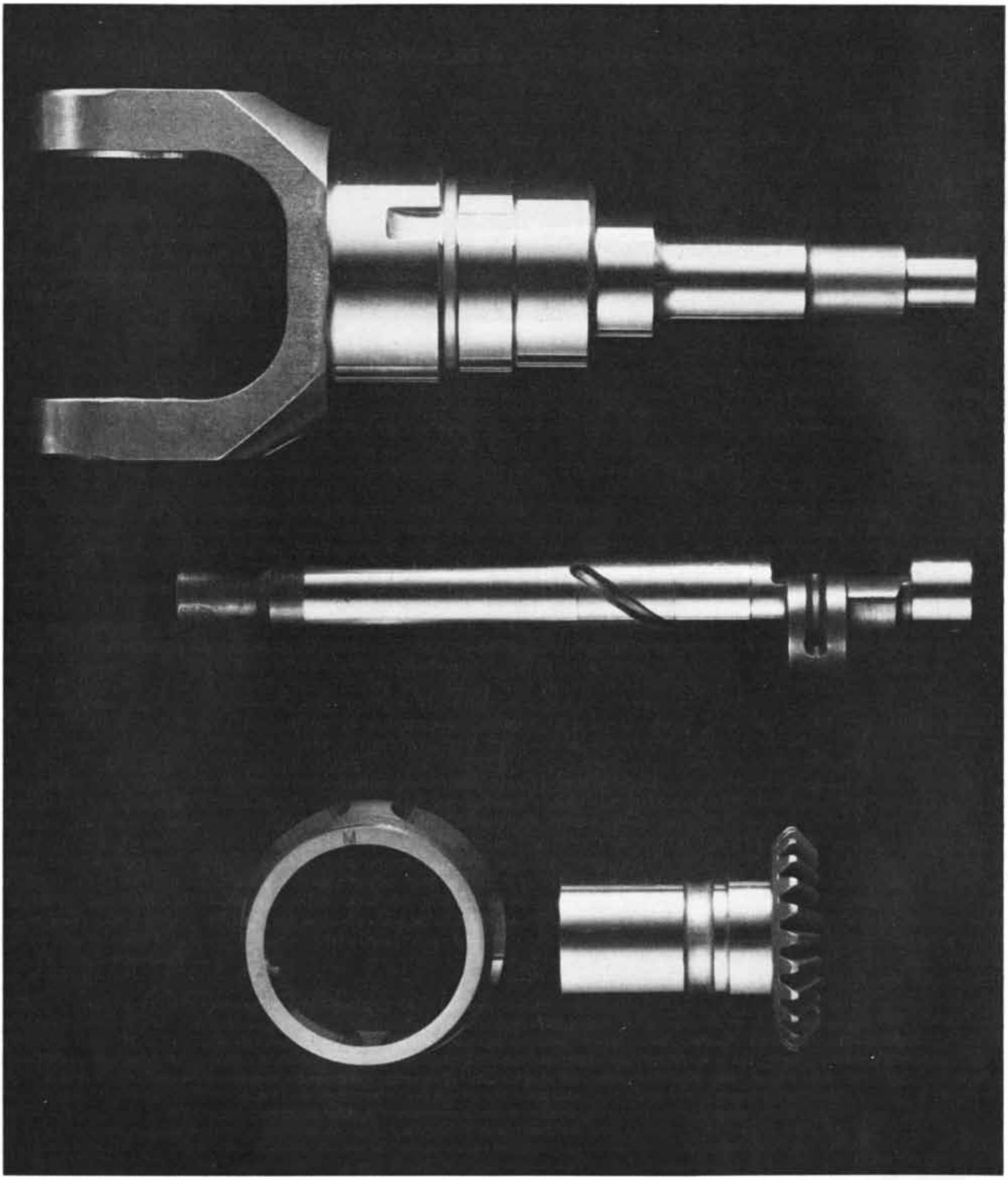
Phenomena that occur as the abrasive enters and leaves the workpiece could now be significant. They probably cannot be safely ignored, as they can be in unidirectional abrasion. Another important difference from simple abrasion is that the abrasive particles in a grinding wheel are cemented together in a random array. The surface of the wheel is periodically dressed, or machined, to the desired shape with a tool of a hard material, usually diamond. This machining entails a fracturing of the individual abrasive particles. As a result the active abrasive points are in general much blunter than the points in a coated abrasive.

The distribution of the rake angles of the abrasive particles touching the surface of the workpiece can be determined by the same methods I have described for coated abrasives. The points generally have more highly negative angles than the particles in a coated abrasive. Our simple model would then predict that only a few percent at most of the abrasive points would operate in a cutting mode on steel, provided the critical rake angle was indeed the zero degrees determined in the simulation experiments with *V*-point tools. The implication, then, is that the efficiency of removal of material would be extremely small.

As I have indicated, however, it is particularly difficult to establish a value for

the critical rake angle of steel, because the value is affected markedly both by lubricants and by the temperature attained in the surface layers of the workpiece. It may also be affected by the speeds attained in grinding, by the smaller depth of the cut and by the differences in the geometry of the interaction. Indeed, it would seem that the entire concept of the critical angle requires validation under conditions of real grinding.

We have done experiments of this kind by cementing a single abrasive particle to the periphery of a metal disk. We measure the rake angle of the particle and make up disks in which the points have a range of rake angles. We then "grind" a workpiece with such a disk under conditions that are otherwise the same as the ones in industrial grinding,



VARIETY OF PARTS given their final shape by grinding appear in these photographs. At the top is an aircraft yoke, at the center a crankshaft for a refrigerator compressor. At the bottom are a ball cage for a universal joint that functions in a front-end drive for automobiles (*left*) and a bevel gear for an aircraft (*right*). The yoke, the crankshaft and the gear were ground on machines made by Cincinnati Milacron, Inc.; the ball cage was ground on a machine made by Bryant Grinder Corporation. Yoke is 8.5 inches (21.6 centimeters) long.

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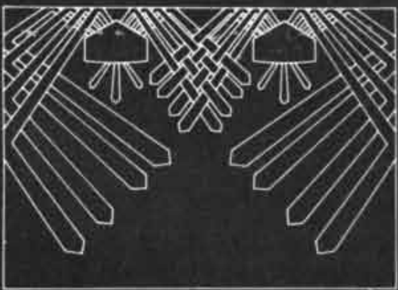

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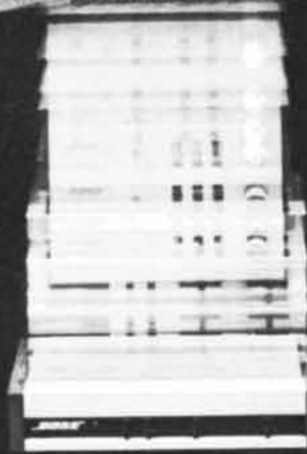

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and we collect the fragments of workpiece material that are thrown off.

The experiments show that ribbonlike chips are indeed produced only when the abrasive points have rake angles more positive than a certain value, which is a characteristic of the workpiece material. The angles so determined are similar to the ones found in simulation experiments. For example, it is -45 degrees for brass, which is the same as it is in the simulation experiment, and -10 degrees for steel, which is only a little more negative than it is in the simulation experiment. This new value for steel predicts that about 10 percent of the abrasive points in the grinding wheel I have described would operate in a cutting mode with steel.

A second important result obtained in these experiments is that some fragments are thrown off when the rake angle is more negative than the critical value. They are, however, small, chunky particles that seem to be prows that have broken off where the abrasive point leaves the surface of the workpiece. In both steel and brass these particles are produced with rake angles down to about -70 degrees. This finding implies that a large proportion of the abrasive points in a grinding wheel do remove material, but as a result of prow formation in a plowing mode. The removal of material by such a mechanism would still be highly inefficient and would consume much energy, but it does represent a method of removing material even if no points are operating in a cutting mode. The prow type of removal would be difficult to analyze because of the difficulty in predicting the volume of the prow formed under given circumstances. In any event the advantage of arranging the conditions of grinding so that the largest possible number of abrasive points operate in the cutting mode is still apparent.

What we really need to be able to do to validate our model is to determine under real grinding conditions the proportion of points that operate in a cutting mode and the proportion that operate in a plowing mode, as we have done for simple abrasion. We could then compare the figures with predictions made by the model. It is unfortunately quite difficult to do these things experimentally, but we are pursuing certain promising approaches.

One thing that can be done is to collect the fragments of workpiece material thrown off by the grinding wheel in a practical grinding operation. When steel is being ground, this debris always consists of a mixture of long ribbons, which are certainly chips, and small chunky particles, which are probably prows. We need to determine the proportion of the two in order to check our model.

Nevertheless, the model does seem, at least in principle, to be applicable to

grinding. Certainly it seems to point the way to minute features of the grinding process that warrant further study. It suggests, for example, that one could profitably study methods of obtaining a more favorable distribution of rake angles in a grinding wheel, either by improving the abrasive or by improving the wheel-dressing practice. It would also be interesting to establish how a favorable distribution of rake angles could be maintained when the abrasive points fracture in use. Another possible approach could be to determine the conditions that ensure the most favorable possible value for the critical rake angle. This knowledge might improve not only the efficiency of grinding but also the control of the process, which is sometimes even more important.

Abrasion can be said to lie at the center of the spectrum of abrasive machining, and grinding can be positioned at the coarse end. At the fine end lie a series of processes that can be termed mechanical polishing. They employ abrasive particles of small diameter that are not cemented together but rather are held loosely on a soft backing. In a typical process an abrasive powder is mixed with a liquid to form a slurry, which is applied to a cloth disk held on a rotating wheel. The workpiece is held against the cloth under a light load, and the two are rotated relative to each other. In another typical process, which is quite common in the metal-finishing industry, the abrasive is held by a soft wax on the periphery of a rotating disk composed of layers of cloth stitched together. The objective of all the processes is to produce a bright, mirrorlike surface.

One tends to think of a polished surface as being quite different from an abraded or a ground one, but it is not. Lord Rayleigh, who developed the theory of the diffraction of light, pointed out many years ago that the only requirement for a surface to reflect light like a mirror is that the roughness of the surface be small compared with the wavelength of the incident light. This result can be achieved in many ways. In my view fine cutting is one of them; moreover, I believe it is the dominant mechanism for polishing methods that employ abrasives in the manner I have described.

There can no longer be any doubt on the first point. It is now possible to produce highly reflecting surfaces with a precisely controlled geometry by lathe turning. Certain precautions are required: the lathe must be rigid and must operate at a high speed with a low level of vibration, and the cutting tool must have a diamond point with carefully prepared cutting edges. The fact remains that the process is lathe turning, which removes material by cutting a chip. The precautions are necessary only to ensure that the machining marks

are exceptionally shallow and closely spaced. In fact, the marks are so shallow and closely spaced that they can scarcely be detected by the best microscopy.

Polished surfaces produced by the action of abrasives have closely spaced shallow grooves differing only in degree from the grooves produced by grinding and abrasion. Moreover, material is removed at a significant rate; again the difference is only one of degree.

We have been able to obtain evidence of two kinds to show that the material removed in polishing results essentially from the chip-cutting process I have described for abrasion and grinding. First, termination of the grooves produced in the surface of a workpiece by a polishing operation can be examined by the technique described for abrasion. Many of the grooves do end in a chip, which differs only in dimensions from the kind of chip produced by abrasion (or by lathe turning).

Second, the debris that collects on a polishing cloth can be extracted and examined. The transmission electron microscope reveals that the particles have most of the characteristics of machining chips from the same type of metal. Again the difference between polishing on the one hand and grinding and abrasion on the other is only one of degree. The essential difference, we suggest, is that the abrasive particles in a polishing operation are characteristically held in such a way that only a very small load can be applied to each one. Hence the point of each particle goes only a small distance into the surface of the workpiece, producing an exceedingly shallow groove.

Since most of the particles are quite loosely held, it is probable that few of the many particles in a polishing mixture do anything useful. The implication is that the efficiency of polishing operations could be greatly improved if a way could be found to hold more of the abrasive particles against the surface of the workpiece in a cutting attitude while still making certain that each one can cut only a shallow groove. We have achieved some success in this direction with an ordinary grinding wheel in which the depth of cut is kept to an appropriately small value.

Our model, which simplifies the shape of an abrasive point as a pyramid, therefore takes us a certain distance toward an understanding of the physics of an entire spectrum of abrasive-machining processes. It certainly seems to be capable of identifying the factors of major importance and the ones that warrant further study with the objective of improving the machining techniques. Still, abrasive machining emerges as a most complicated process, which will be difficult to understand fully even in the long term.

The Reward System of the Brain

Two decades ago it was discovered that the brain has "pleasure centers." These centers are now seen as belonging to a system of pathways that appear to play a role in learning and memory

by Aryeh Routtenberg

Neuroscientists have learned much about the anatomy, physiology and chemistry of the brain. Does this knowledge relate to human learning, pleasure and mood? Is it possible that these complex processes are mediated by specific brain pathways and specific chemical substances? The answer appears to be yes, largely as a result of an intriguing but puzzling discovery made some 20 years ago at McGill University by James Olds and Peter Milner. They demonstrated that a rat with an electrode inserted into a certain area of its brain would press a treadle to stimulate itself [see "Pleasure Centers in the Brain," by James Olds; SCIENTIFIC AMERICAN, October, 1956]. Olds, a pioneer in the study of the relation between brain function and behavior, died in a swimming accident in 1976; his death was particularly tragic because he was engaged in exciting new explorations of brain physiology.

The phenomenon discovered by Olds and Milner, which is now referred to as brain reward, can be localized in particular nerve cells and their fibers. The brain-reward system is affected by drugs that interact with the substances secreted by these nerve cells. The fact that only certain nerve-fiber pathways are implicated in brain reward suggests that these pathways have a specific function. This parallels what is known of the visual system and the movement system, each of which has a specified set of component pathways.

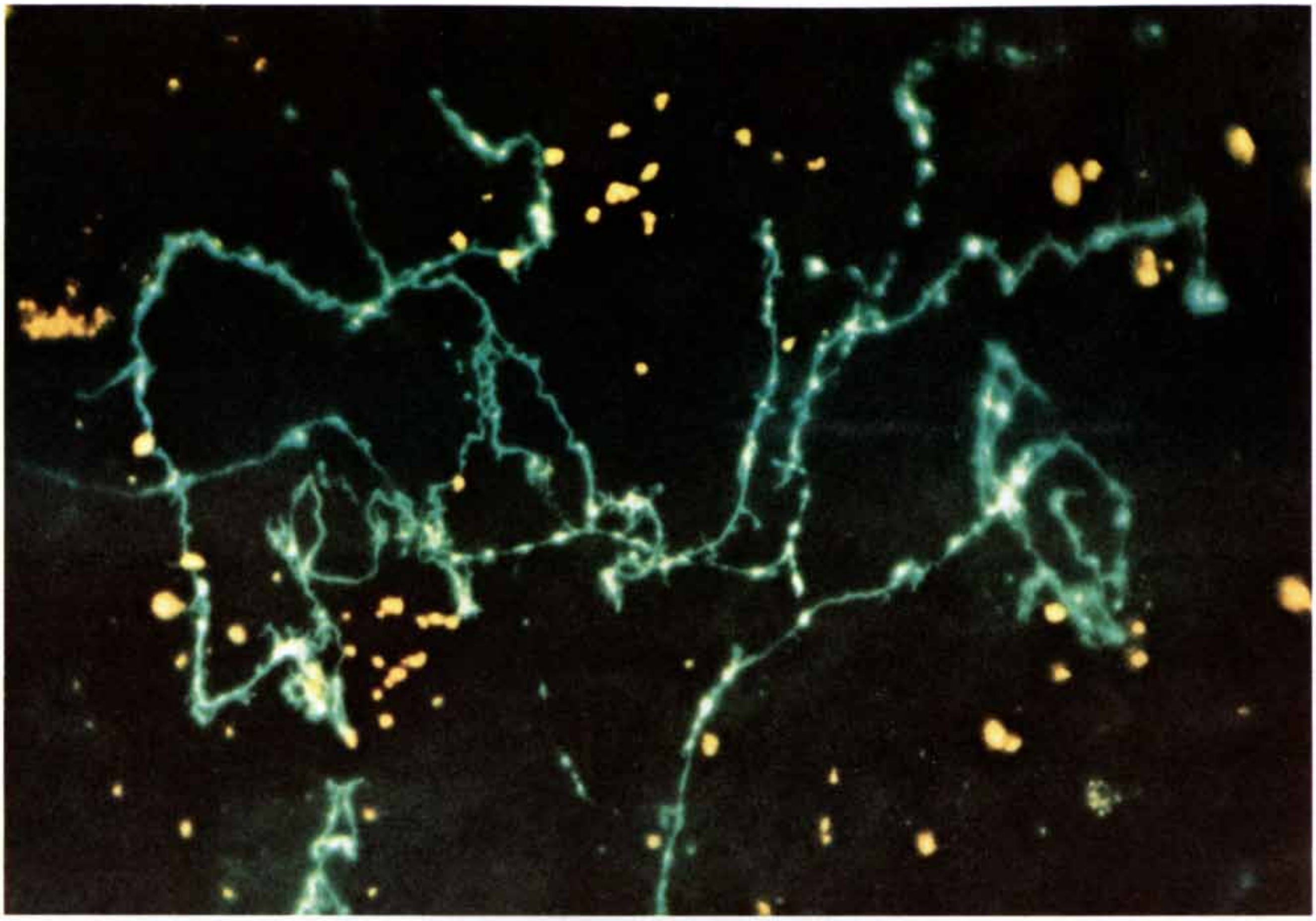
Olds, first at the University of California at Los Angeles and then at the University of Michigan, took the initial steps toward identifying the pathways that support brain reward. He confirmed that self-stimulating behavior in laboratory animals is prompted only by the stimulation of particular brain areas and is not a general effect due simply to the electrical stimulation of brain tissue. For example, stimulation of the medial forebrain bundle, a group of nerve fibers that pass through the hypothalamus, gave rise to the highest rates of treadle-pressing in response to the lowest electric currents: shocks from electrodes in this area could produce response rates of more than 100 presses a minute. There were also areas characterized by milder effects; for example, stimulation of the septal area caused the animals to respond only about 10 times a minute.

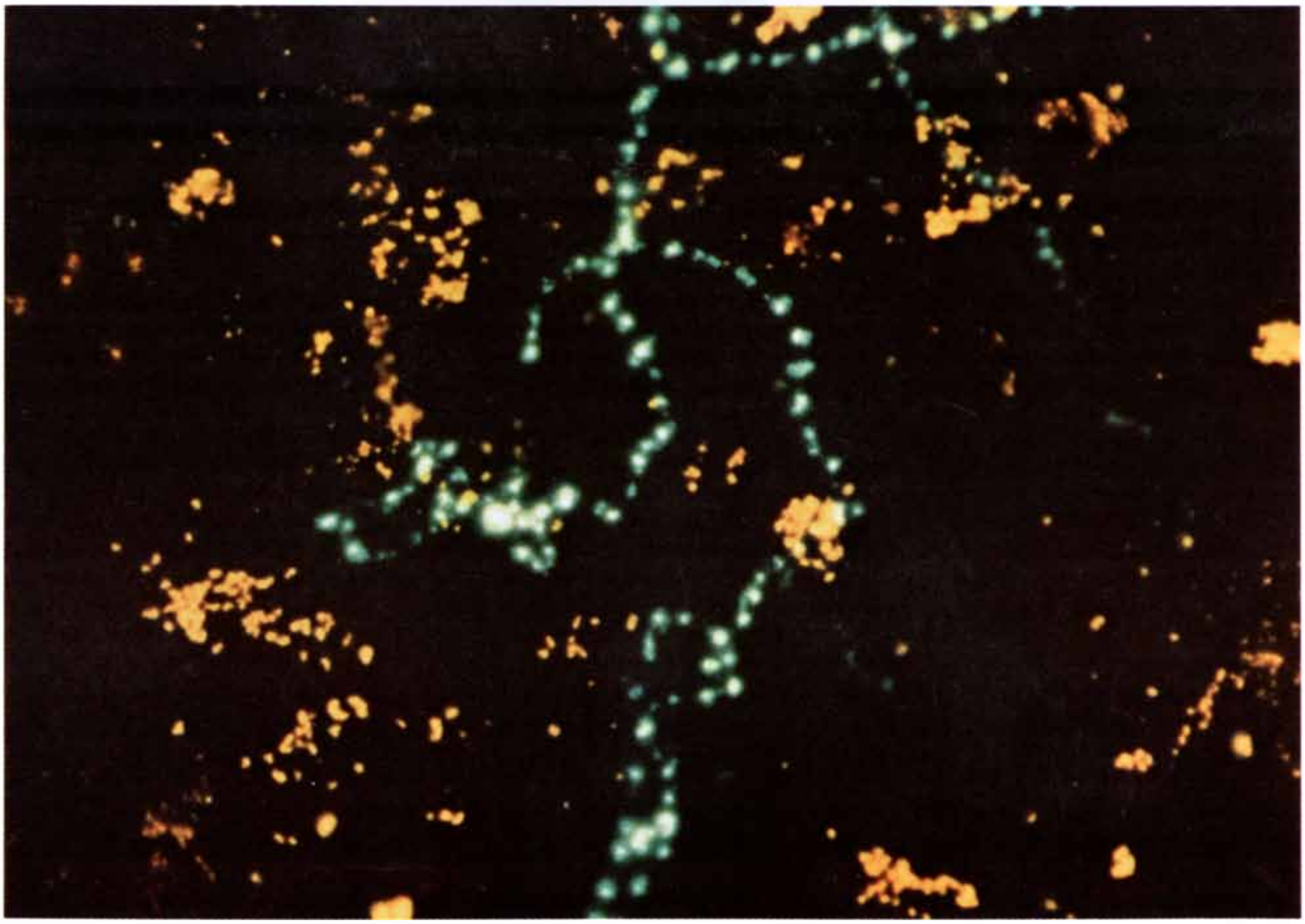
In 1962, while working in Olds's laboratory, I became interested in these different response rates for stimulation of different brain regions and set about studying them. A rat was given a choice between two treadles, one delivering rewarding brain stimulation and the other delivering the only food available to the animal during the experiment. I found that the animals would forgo food essential to their survival in order to obtain brain stimulation. This behavior was observed, however, only if the electrode was within the medial forebrain bundle. If the electrode was as little as half a millimeter away from this area, or in other areas whose stimulation yielded a reward, such as the septal area, the animals pressed both the food-delivering and the brain-stimulation treadles and were able to maintain their body weight and survive.

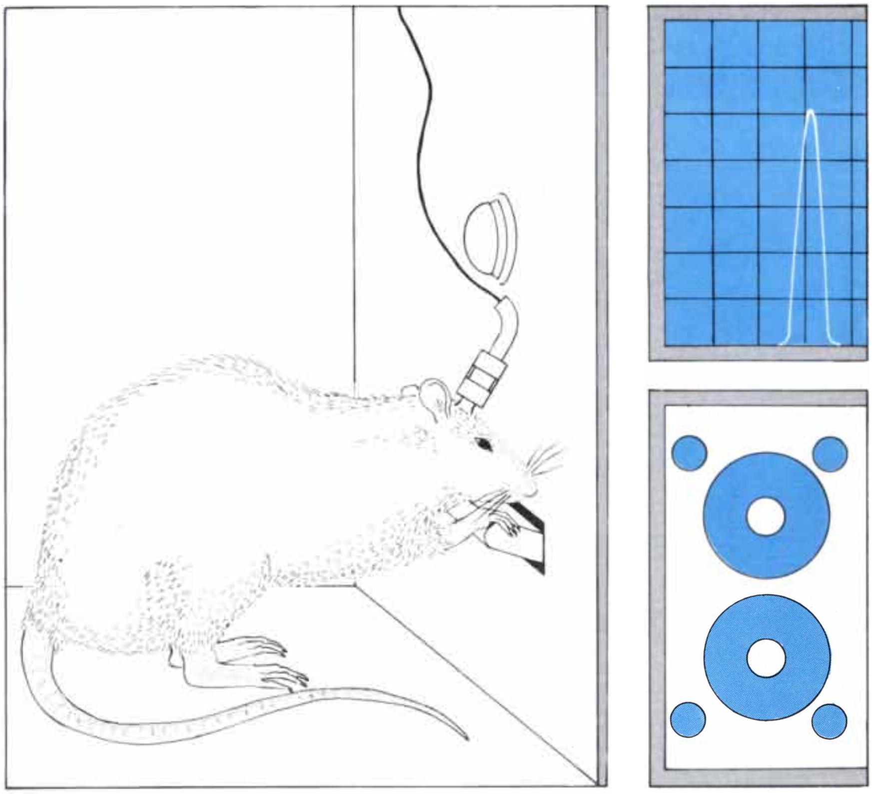
I wondered whether an animal more intelligent than the rat, if it were placed in the same situation, would show the same maladaptive behavior or whether its more highly developed cerebral cortex would enable it to achieve a balance between self-stimulation and feeding. Eliot Gardner and I were able to demonstrate self-starvation in the rhesus monkey, an animal with a cortex far more advanced than that of the rat. This powerful effect implies that higher primates, perhaps even human beings, will stop eating in order to obtain rewarding brain stimulation. Such results suggest that the neural mechanisms subserving self-stimulation exert a powerful and perhaps dominant influence on behavior, particularly activities of the moment. Since the behavior is so compulsive, one wonders whether the reward system may play a role in drug addiction. For example, there is some evidence that certain regions of the brain that are sensitive to morphine and contain the morphinelike substance enkephalin are in the same location as the regions supporting brain reward.

The brain's functioning is obscured by its enormously complex array of nerve cells and their fibers, and so in order to identify the cells involved in self-stimulation it is necessary to combine the study of brain reward with the study of brain anatomy. In my laboratory at Northwestern University we have been pursuing this approach by making lesions with the stimulating electrode under light anesthesia at brain sites in rats where self-stimulation has been demonstrated. Within a few days the neural elements near the tip of the stimulating electrode begin to degenerate. We then perfuse the animals with formaldehyde, use a special stain for degenerating tis-

TWO TYPES OF NERVE FIBERS in the frontal cortex of the human brain are revealed in the fluorescent micrographs on the opposite page. The images were obtained by chemically treating thin sections of brain tissue so that the neurotransmitter substances in the nerve fibers fluoresced when they were illuminated with ultraviolet radiation. This technique has been an essential tool in mapping the neural pathways that mediate brain reward. The micrograph at the top shows a nerve fiber containing the neurotransmitter dopamine. The green-fluorescent dopamine fiber is typically thin and sinuous, with irregularly spaced spindle-shaped swellings. (The bright yellow blobs in the background represent not neurotransmitter but granules of the fatty pigment lipofuscin, which are present in many cell types and fluoresce in the absence of chemical treatment.) The micrograph at the bottom shows a nerve fiber containing the neurotransmitter norepinephrine. This fiber too has a green glow, but it can be distinguished from the dopamine fiber by the closely spaced swellings, which are intensely fluorescent. Both the dopamine and the norepinephrine pathways in the frontal cortex have been implicated in the reward system of the brain. These micrographs, magnified approximately 1,000 diameters, were made by Brigitte Berger of Neuropathology Laboratory at Pitié-Salpêtrière Hospital in Paris.







SKINNER-BOX APPARATUS is utilized to study the behavioral effects of brain reward. A metal electrode is implanted in the reward system of the rat, and the animal is allowed to trigger an electric stimulus to its brain by pressing the treadle. The curve on the oscilloscope screen indicates the delivery of the stimulus. If the stimulating electrode is implanted in the medial forebrain bundle of the hypothalamus, the rat will stimulate itself nearly continuously for days, neglecting food, water and sleep. Other parts of reward system give rise to less dramatic effects.

sue and see which neural elements are associated with the reward effects.

An example of this approach linking self-stimulation to specific pathways is provided by our study of the cerebral cortex in the frontal lobe of the brain. Although it had been doubted that the frontal cortex was important to brain reward, there are two regions of it in the rat that we have found to support self-stimulation. We made lesions at frontal-cortex self-stimulation sites and traced a pathway through the caudate nucleus and the internal capsule on its medial side. At the level of the hypothalamus this pathway is intermingled with the medial forebrain bundle. This work offers evidence that brain reward in the medial forebrain bundle results from stimulation of these frontal-cortex fibers. There is reason to believe from other work that this system may be only one of several brain-reward systems passing through the medial forebrain bundle.

The involvement of the frontal cortex in brain reward has been demonstrated in monkeys as well as in rats. Edmund Rolls of the University of Oxford has discovered self-stimulation points in the frontal cortex of the squirrel monkey similar to the regions that have been mapped in the rat. Even though the brain locations where self-stimulation has been observed are similar in a rodent (the rat) and a primate (the squirrel monkey), the great difference among species in the size of the frontal cortex creates the potential for great variation in the significance to a given species of brain-reward stimulation.

Brain reward can be found not only in the frontal cortex and the hypothalamus but also deep within the brain stem: in the pons and the medulla. Such findings indicate that although brain reward is present only at specific locations, it extends from the forebrain to the midbrain and into the hindbrain. In 1969 Charles Malsbury and I showed that self-stimulation could be obtained with electrodes positioned in the output pathway of the cerebellum and at sites in the dorsal pontine tegmentum of the brain stem. Some of these regions were also close to newly discovered pathways that were associated with catecholamine neurotransmitters: substances that transmit the nerve impulse from one nerve cell to another. We therefore began to suspect that neurotransmitters of this type were involved in self-stimulation.

In 1971 Urban Ungerstedt of the Karolinska Institute in Stockholm described new catecholamine pathways in the forebrain, the midbrain and the hindbrain. He worked with the technique known as histofluorescence, in which the location of specific substances in a tissue is revealed by inducing them to emit light of a characteristic color. The technique was developed in 1962 by B. Falck of the University of Lund and N.-Å. Hillarp of the Karolinska Institute, who built on earlier work by O. Eränkö of the University of Helsinki and Arvid Carlsson of the University of Göteborg. In 1974 Olle Lindvall and Anders Björklund of the University of Lund applied more sensitive techniques to establish the existence in the central nervous system of mammals of several pathways associated with the catecholamine norepinephrine and several pathways associated with another catecholamine, dopamine.

To obtain histofluorescent micrographs of brain tissue the tissue is first treated with aldehyde or glyoxylic acid, which react with catecholamines to form fluorophores, substances that fluoresce when they are excited by ultraviolet radiation. When a thin section of the tissue is exposed to ultraviolet in the fluorescence microscope, the fluorophore is excited and emits light. With the aid of a special wavelength detector norepinephrine can be seen to emit in the green-yellow region of the spectrum and dopamine in the green region. Although the color difference is difficult to determine without a special detector, the shape of the nerve fiber containing one substance or the other is different. Thus when the fluorescent fibers are observed in a histofluorescent micrograph, they reveal the anatomical location of the chemical substance. The histofluorescence technique is therefore based on histochemical principles: it is chemical in that it reveals brain pathways through a chemical reaction with neurotransmitters and histological in that the reaction takes place in a thin section of brain tissue on a microscope slide.

The existence of catecholamine pathways has been confirmed by the application of histofluorescence to the human brain. Working with tissue from an unviable fetus, Lars Olson, L. O. Boréus and Ake Seiger of the Karolinska Institute and Hospital have found the analogous catecholamine brain pathways in humans that have been observed in the brain of rats and monkeys.

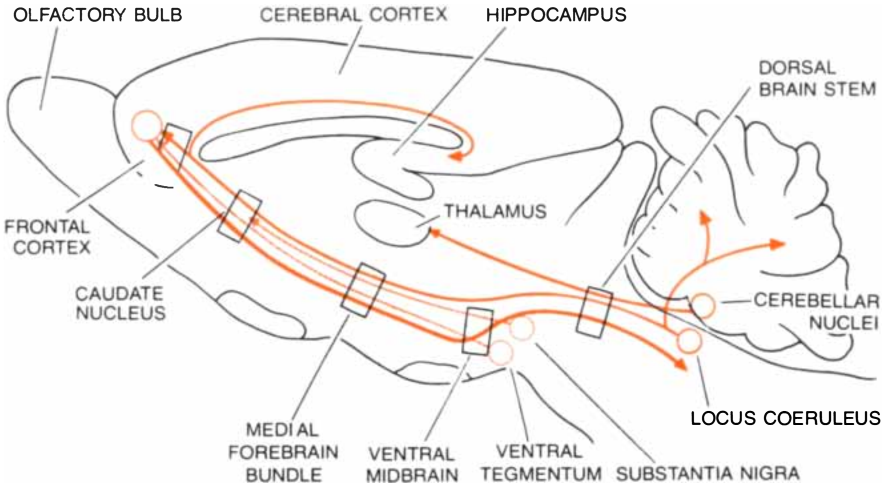
The evidence for the similar location of catecholamine pathways and areas of self-stimulation is not the sole reason for supposing there is a connection between catecholamines and the brain-reward system. The rate at which rats with an electrode implanted in their brain will press a treadle to stimulate themselves is affected by certain drugs that are known to interfere with the function of catecholamines. The same drugs are also known to affect mood in human beings; indeed, they are sometimes

administered to control anxiety and psychotic behavior. Since there is a connection between these mood-altering drugs and the catecholamines and also between the catecholamines and the brain-reward system, there would seem to be one between the brain-reward system and mood and personality.

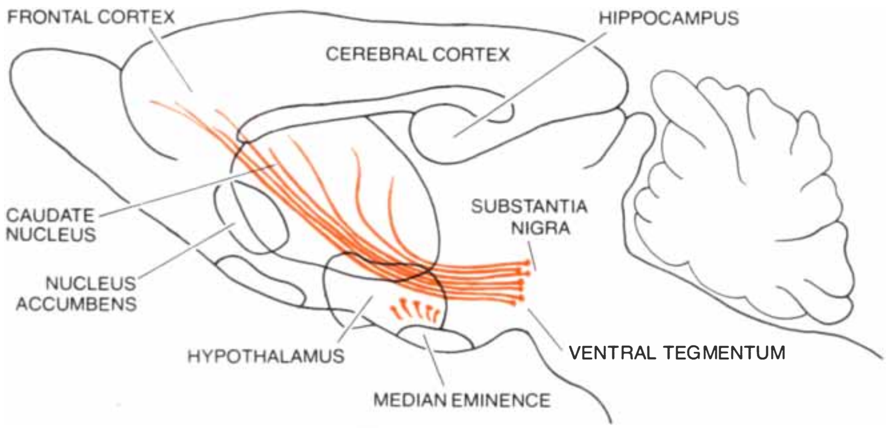
Norepinephrine and dopamine are two major catecholamines that have been identified as neurotransmitters in the brain. When a nerve cell in a catecholamine system is activated, it releases one of these substances. The neurotransmitter crosses the synapse, the gap between the axon terminal of one nerve cell and the cell body of the next nerve cell. In so doing it changes the permeability of the membrane of the second nerve cell to ions in the extracellular fluid and so changes its excitability. The catecholamine is then either destroyed by an enzyme or is taken back into the axon terminal of the first cell.

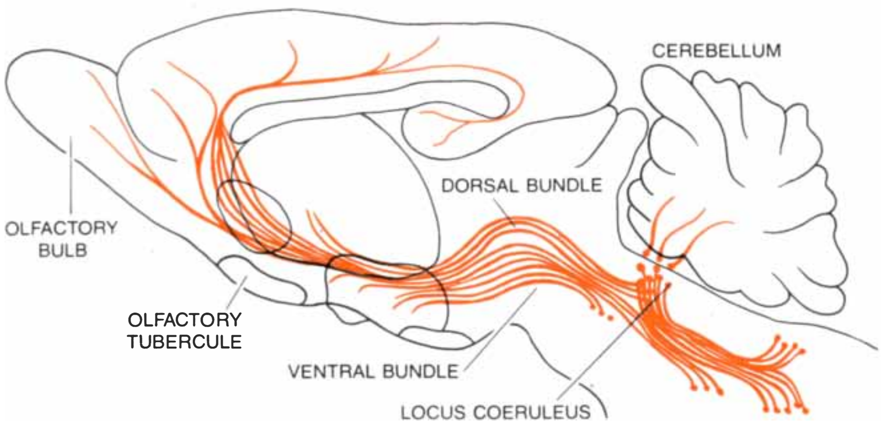
Drugs that manipulate the catecholamine system have a powerful effect on mood. It is generally believed such drugs act to modify catecholamine transmission at the synapse, thereby altering the neurotransmitter's ability to influence other nerve cells. Studies involving a variety of drugs that modify catecholamine synaptic transmission have revealed a straightforward relation: agents that elevate catecholamine levels or mimic the action of catecholamines facilitate self-stimulation; agents that lower these levels depress self-stimulation. For example, the drug *d*-amphetamine potentiates both the action of catecholamines and self-stimulation. The drug chlorpromazine blocks the action of catecholamines and also blocks self-stimulation.

Chlorpromazine has been effective as an antipsychotic agent, and so a link has been suggested between psychoses and the catecholamine-connected self-stimulation pathways. It seems possible that because of either genetic or environmental factors abnormalities in the brain-reward pathways could lead to permanent changes in mental state. Larry Stein and C. David Wise of the Wyeth Laboratories have suggested that the cause of schizophrenia is an enzymatic deficiency that allows the production of a toxic substance, 6-hydroxydopamine, which destroys norepinephrine pathways thought to be associated with brain reward. They argue that these pathways, which can be seen in histofluorescent micrographs, are essential for adaptive behavioral responses. In support of their hypothesis they have demonstrated that synthetic 6-hydroxydopamine injected directly into the brain of a rat reduces the rate at which the rat presses a treadle to get a brain reward. This hypothesis is of special value because it explicitly relates schizophrenia to abnormalities in particular brain-reward pathways that

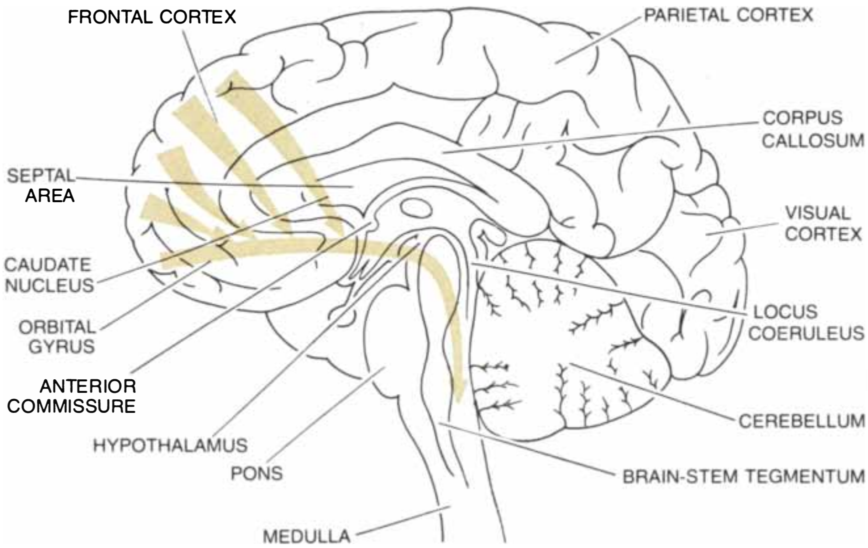


PATHWAYS OF REWARD in the rat brain are outlined schematically in this longitudinal section. The pathways extend in both directions from nerve-cell bodies in the hindbrain, the midbrain and the frontal cortex, passing through the medial forebrain bundle in the hypothalamus. The circles indicate the locations of the cell bodies; the rectangles indicate regions where reliable self-stimulation behavior has been obtained in studies with the Skinner-box apparatus.

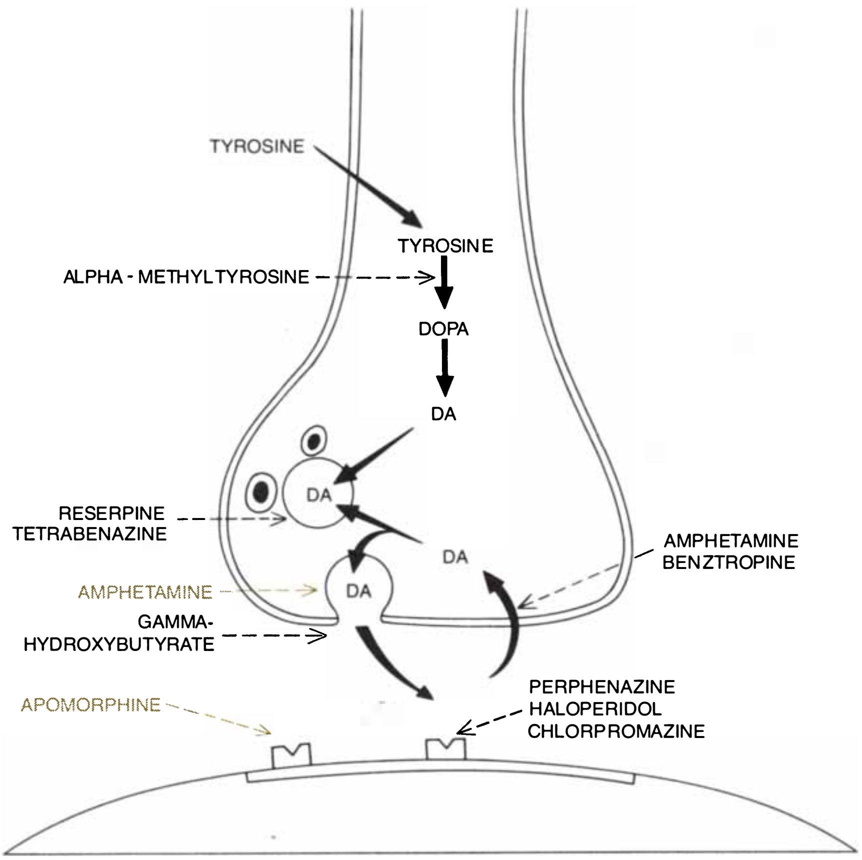




NEUROTRANSMITTER PATHWAYS implicated in the reward system of the rat brain were mapped by fluorescence microscopy. The nerve cells that secrete dopamine (*top*) have their cell bodies concentrated in the substantia nigra and the ventral tegmentum of the midbrain; their axons project primarily to the caudate nucleus, the frontal cortex and the entorhinal cortex. The nerve cells that secrete norepinephrine (*bottom*) have their cell bodies localized primarily in the locus coeruleus of the brain stem; they project to the cerebellum, the cerebral cortex and the hypothalamus. Both the norepinephrine and the dopamine systems overlap much of the area that gives rise to self-stimulation behavior in rats. The dopamine fibers are found only in areas that mediate brain reward, whereas the norepinephrine fibers extend into other regions. This and other evidence points to a more critical role for dopamine in brain reward.



REWARD SYSTEM OF THE HUMAN BRAIN has been roughly localized in the regions shown in color. These areas correspond to the parts of the rat brain that support self-stimulation behavior. As in rodent brain, the pathways extend between hindbrain and frontal cortex.



DOPAMINE TRANSMISSION across the synapse, the tiny gap between the terminal of one cell and the receptive surface of another, can be enhanced or inhibited by psychoactive drugs. Thus the effects of these drugs on self-stimulation behavior shed some light on the neurochemical mechanisms underlying brain reward. Inhibitory drugs are shown in black, enhancers in color. Dopamine transmission can be inhibited by agents that block its synthesis (alpha-methyltyrosine), prevent its storage in vesicles (reserpine, tetrabenazine), prevent its release (alphahydroxybutyrate) or block its attachment to receptor sites on the postsynaptic membrane (perphenazine, haloperidol, chlorpromazine). Dopamine transmission is enhanced by drugs that increase its release (amphetamine, cocaine), facilitate receptor activation (apomorphine) or inhibit reuptake of dopamine into the terminal from the synapse (amphetamine, benztropine).

contain a particular transmitter substance.

A question that has generated much interest among investigators of brain reward has to do with possible differences among the roles played by different catecholamines. Various hypotheses have been put forward: that self-stimulation is mediated solely by either norepinephrine or dopamine, that they are both involved but independently, or that they act in concert. Ronald M. Clavier and I have approached the problem anatomically. We examined the contribution made to self-stimulation by two major norepinephrine systems known as the dorsal and ventral bundles. First we demonstrated that self-stimulation in the brain stem is associated with the dorsal norepinephrine bundle. We made lesions at sites that supported self-stimulation and found they gave rise to a change in the histochemical fluorescence of the dorsal bundle, indicating that this region is associated with pathways that mediate brain reward. Similar changes in the histochemical fluorescence of the ventral bundle resulted only from lesions in brain areas that were not involved in self-stimulation. Therefore whereas the ventral bundle is not associated with brain reward, the dorsal norepinephrine bundle does appear to be associated with it.

Even though the dorsal bundle is associated with self-stimulation, is it an essential component of the brain-reward system? If brain reward results from an activation of the axons in the dorsal bundle, one would expect that the destruction of the nerve-cell bodies of these axons, which are found in an area called the locus coeruleus, would reduce self-stimulation. Clavier and I found this did not happen: the almost total destruction of the locus coeruleus had little effect on the rate of self-stimulation in rats. Interestingly enough, however, a lesion limited to the medial forebrain bundle drastically reduced self-stimulation. This effect may be related to the medial forebrain bundle's acting as a "pleasure relay station" for other brain pathways that do not contain norepinephrine.

These results indicate the norepinephrine pathways may not be critical to self-stimulation. That a dopamine system plays a more crucial role is suggested by the fact that the lesion in the medial forebrain bundle reducing self-stimulation also damaged two components of the dopamine system in the midbrain: the ventral tegmentum and the substantia nigra, pars compacta. Olds and Ephraim Peretz had shown in 1960 that the ventral tegmentum could support self-stimulation, and Malsbury and I, surveying the midbrain, the pons and the anterior medulla, had demonstrated in 1969 that the highest rates of self-stimulation were obtained from electrodes placed in the ventral tegmentum.

We also discovered brain reward in the other component of the dopamine system, the substantia nigra, pars compacta. Yung H. Huang, who was then a graduate student in my laboratory, demonstrated the involvement of the substantia nigra by means of low currents delivered through electrode wires that were considerably smaller than those implanted in earlier experiments. C. L. E. Broekkamp of the University of Nijmegen has shown that self-stimulation in the substantia nigra is blocked by the injection into the caudate nucleus of the drug haloperidol, which selectively blocks dopamine transmission. Self-stimulation is increased by the injection of amphetamine, which enhances dopamine transmission. These results indicate that the drugs influence brain reward by acting on nerve cells in the caudate nucleus. They also indicate an important role for dopamine systems in self-stimulation mechanisms.

It has been learned only recently that both norepinephrine and dopamine systems send their axons into the cerebral cortex. This finding is a critically important one because it relates the cerebral cortex to primitive structures deep within the midbrain and hindbrain that arose much earlier in the evolution of the brain. It raises the possibility that the highly complex and intricate patterns of intellectual activity in the cortex are influenced by evolutionarily primitive catecholamine systems.

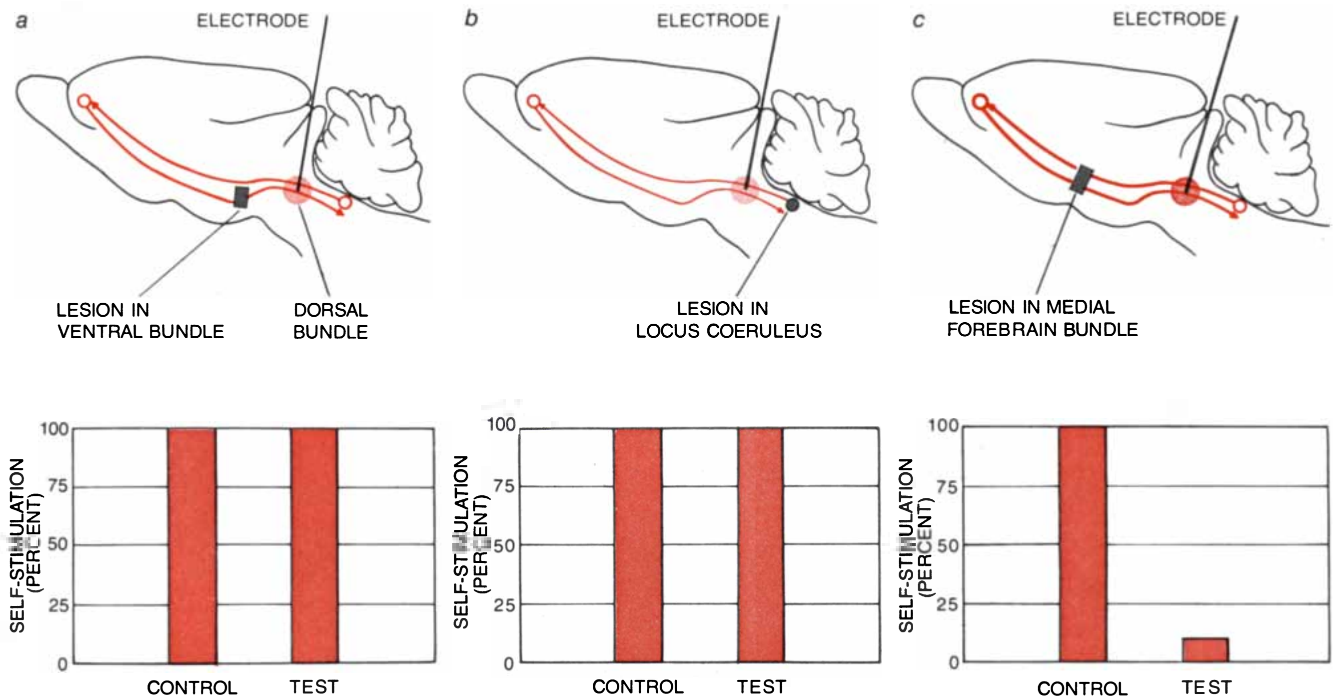
By exploiting recent improvements in the sensitivity of the fluorescence technique it is now possible to distinguish between norepinephrine axons and dopamine axons in the cerebral cortex of both experimental animals and man. There are differences in the visual appearance of the two networks: the norepinephrine fibers are thicker and have more swellings than the dopamine fibers, which are thin and sinuous.

Although both catecholamine systems are found at self-stimulation sites, the norepinephrine system is distributed evenly throughout the layers of the frontal cortex and is found in areas where self-stimulation cannot be demonstrated. The dopamine system, on the other hand, has been shown by Brigitte Berger, Ann-Marie Thierry and Jacques Glowinski of the Collège de France to be unevenly distributed, with its highest concentration of axons and axon terminals located in the medial and sulcal cortex: precisely those areas in the frontal cortex where brain reward was observed. Recently Timothy Collier and I have studied islands of dopamine fluorescence in the entorhinal cortex, a region of the temporal lobe where we have demonstrated brain-reward effects.

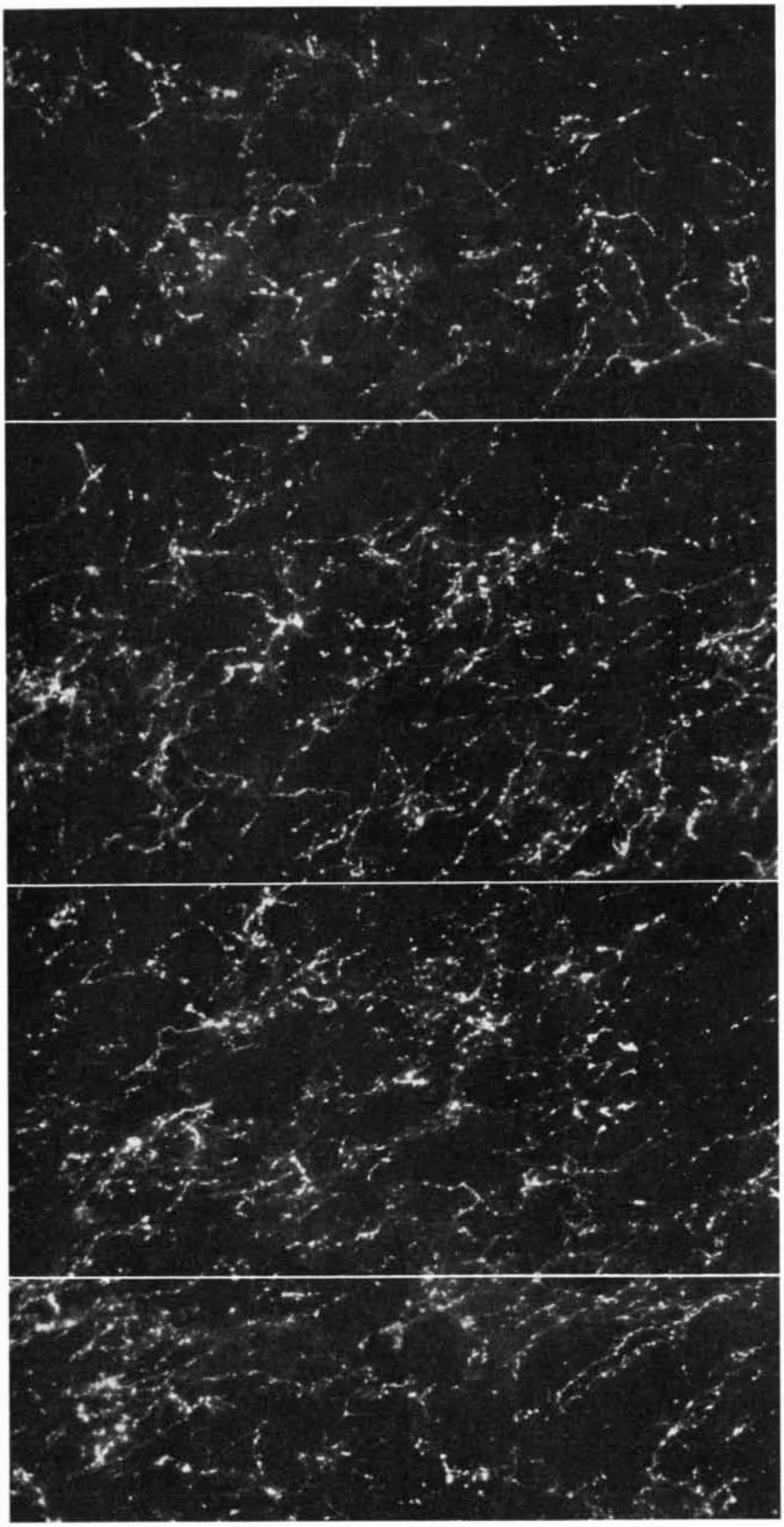
The involvement of certain regions of the cerebral cortex in self-stimulation may therefore be related, at least in part, to their input from dopamine systems. It is tempting to think that dopamine-affecting drugs that manipulate mood and alleviate psychotic behavior may achieve part of their effect through those catecholamine systems of the cortex that support brain reward.

The fact that our recent brain-reward studies have implicated the entorhinal cortex as an area supporting self-stimulation is one of considerable interest. Fibers in this region project to the hippocampus, a brain structure thought to be involved in the formation of memory and recently shown to be connected with memory of spatial relations. A connection between brain reward and learning has been recognized since 1961, when Olds and his wife Marianne E. Olds showed that the stimulation of reward sites disrupted learning in experimental animals. Since then neuroscientists have gained in their understanding not only of the link between reward and learning but also of the role played by the self-stimulation pathways in memory formation.

I have speculated that the pathways of brain reward may function as the pathways of memory consolidation. By this I mean that when something is learned, activity in the brain-reward pathways facilitates the formation of memory. If these pathways are electrically stimulated in the course of the learning process, in effect jamming the circuits and altering the normal physiological activity associated with the process, one would expect memory of what is being learned to be impaired. This expectation has been confirmed



EFFECTS OF BRAIN LESIONS on self-stimulation behavior in the rat were determined in experiments performed by the author and Ronald M. Clavier in the author's laboratory at Northwestern University. An electrode was implanted in the dorsal brain stem of the rat, and the animal was allowed to stimulate itself by pressing a treadle in a Skinner box. Lesions in the ventral bundle of the norepinephrine system (*a*) had no effect on self-stimulation behavior 10 days after surgery, nor did removal of the locus coeruleus (*b*), where the norepinephrine cell bodies giving rise to the dorsal bundle are concentrated. On the other hand, destruction of the medial forebrain bundle (*c*) resulted in a dramatic decline in self-stimulation, suggesting that the dopamine fibers in this region are essential for brain reward.



DOPAMINE FIBERS in the frontal cortex of the rat brain are revealed in this montage of fluorescent micrographs. The surface of the brain is at the top of the montage, with the deep layers at the bottom. Only dopamine fibers appear, because several weeks before the micrographs were taken a lesion was made in the locus coeruleus of the animal that destroyed all the norepinephrine fibers in the frontal cortex. Note that density of dopamine fibers is greatest in deep layers of the cortex. Micrographs were made by Olle Lindvall of the University of Lund.

to a remarkable degree by work I have done with Elaine Bresnahan, Nancy Holzman and Rebecca Santos-Anderson. We found that continuous stimulation of brain-reward regions in the medial forebrain bundle, the substantia nigra or the frontal cortex applied in the course of learning a simple task disrupts the ability of an experimental animal to remember the task 24 hours later. On the other hand, stimulation of the locus coeruleus, which apparently is not involved in brain reward, had no effect on the retention of the task.

The involvement of the substantia nigra in memory processes is surprising because it is usually associated with the control of movement. (A malfunction of the substantia nigra has been specifically related to Parkinson's disease.) Haing-Ja Kim has shown in my laboratory, however, that injections of substances specifically overactivating the substantia nigra cause the release of dopamine and lead to the disruption of memory. It seems likely that the substantia nigra system plays a role in behavioral processes beyond the control of movement and that the system is also important in the formation of memory.

Collier and I found that the entorhinal cortex plays an interesting part in the relation between self-stimulation and memory formation. Artificial stimulation applied to this area during learning has no effect on memory, but when it is applied after learning, it impairs memory. The finding is remarkable because it means brain stimulation does not have the same effect on memory in all brain areas and at all times. The evidence from our research on the entorhinal cortex suggests that stimulation must be applied both in the appropriate brain region and at the right moment in the learning process in order to hinder memory.

One puzzling question raised by this research is that if the brain stimulation is rewarding, why does it impair learning rather than enhance it? The problem is currently being investigated, and it seems the effect is related, at least in part, to how the stimulation is administered. Norman White of McGill has shown that if animals are given the opportunity after learning to press a treadle to get rewarding brain stimulation, rather than receiving it continuously as in our memory-reward experiments, they remember the task better. The improved learning may be due to the fact that the animals self-regulate the amount of stimulation, thereby self-reinforcing their behavior. Other work also supports a view held in my laboratory, namely that this enhancement of memory is to a large extent mediated by the dopamine system of the substantia nigra.

The role of self-stimulation pathways

DRUG	TRADE NAME	NEUROTRANSMITTERS AFFECTED	MODE OF ACTION	EFFECT ON SELF-STIMULATION	EFFECT ON LEARNING AND MEMORY
ALPHA-METHYL-TYROSINE	—	DOPAMINE NOREPINEPHRINE	INHIBITS SYNTHESIS OF CATECHOLAMINES	DECREASES RATE	IMPAIRMENT
RESERPINE	SERPASIL	DOPAMINE NOREPINEPHRINE	PREVENTS STORAGE OF CATECHOLAMINES	DECREASES RATE	IMPAIRMENT
6-HYDROXYDOPAMINE	—	DOPAMINE NOREPINEPHRINE	KILLS NERVE CELLS CONTAINING CATECHOLAMINES	DECREASES RATE	IMPAIRMENT
CHLORPROMAZINE	THORAZINE	DOPAMINE NOREPINEPHRINE	BLOCKS CATECHOLAMINE RECEPTORS	DECREASES RATE	IMPAIRMENT
AMPHETAMINE	DEXEDRINE	DOPAMINE NOREPINEPHRINE	ENHANCES RELEASE OF CATECHOLAMINES INTO SYNAPSE	INCREASES RATE	FACILITATION (AT LOW DOSES)
IMIPRAMINE	TOFRANIL	DOPAMINE NOREPINEPHRINE	PREVENTS REUPTAKE OF CATECHOLAMINES FROM SYNAPSE	INCREASES RATE	UNCERTAIN (INSUFFICIENT INFORMATION)
PHENOXYBENZAMINE	DIBENZYLINE	NOREPINEPHRINE	BLOCKS ALPHA-NOREPINEPHRINE RECEPTORS	DECREASES RATE	UNCERTAIN
PROPRANOLOL	INDERAL	NOREPINEPHRINE	BLOCKS BETA NOREPINEPHRINE RECEPTORS	DECREASES RATE	UNCERTAIN
CLONIDINE	CATAPRES	NOREPINEPHRINE	DECREASES NOREPI-NEPHRINE RELEASE	DECREASES RATE	UNCERTAIN
HALOPERIDOL	HALDOL	DOPAMINE	BLOCKS DOPAMINE RECEPTORS	DECREASES RATE	IMPAIRMENT
APOMORPHINE	—	DOPAMINE	STIMULATES DOPAMINE RECEPTORS	INCREASES RATE	FACILITATION (AT LOW DOSES)

EFFECTS OF PSYCHOACTIVE DRUGS on self-stimulation behavior and on learning and memory in the rat are summarized in this table. Drugs that enhance transmission at dopamine and norepinephrine synapses tend to potentiate self-stimulation behavior; blocking drugs tend to inhibit it. The drugs seem to have parallel effects on learning and memory, although in some cases data are inconclusive.

in learning and memory remains a strong interest of several investigators of brain reward. Before his death Olds had been recording the activity of single nerve cells throughout the brain during learning in freely moving rats, and this research is being continued by Marianne Olds. James Olds had discovered certain nerve cells that "fire" 20 milliseconds or less after the presentation of a cue the animal has learned earlier is a signal for food. A number of these cells were in the substantia nigra, the region my research had connected with brain-reward pathways.

The evidence clearly shows that the brain-reward pathways play an important role in learning and memory. Much of the research strategy in the study of brain reward itself can be applied in this area, including the anatomical analysis of brain pathways and the use of drugs that affect the function of specific neurotransmitters. In this connection it is of considerable interest that certain amphetaminelike compounds potentiating the self-stimulation system are the principal therapeutic drugs prescribed for children with neurological disorders of attention and learning. These considerations suggest that as more is learned about self-stimulation pathways and their relation to learning new therapeutic tools for assisting people with learning and memory disabilities may be discovered.

To sum up, new information about the catecholamine-fiber system has made it possible to chart the brain pathways of self-stimulation as explicitly as the pathways of well-known sensory and motor systems. Evidence for the reward effects of localized electrical stimulation, for the control of brain reward by psychoactive drugs and for the association of reward pathways with memory formation indicates that the neural substrates of self-stimulation play a vital role in the guidance of behavior. And it has been shown that reward systems are present at all levels of the brain, from the medulla oblongata to the cerebral cortex.

Since the time when the medial forebrain bundle alone was designated as the pleasure center, the boundaries of the brain-reward system have been extended deep into the brain stem and far forward into the cortex of the frontal lobe of the cerebrum. All the reward systems do, however, have pathways through the medial forebrain bundle, suggesting that this region of the hypothalamus may be described as the relay station through which the brain-reward pathways course.

It would obviously be highly desirable if brain-stimulation technology and the information derived from the study of the anatomy of the reward system could be applied to the alleviation of neurological diseases caused by disorders of the reward system. Such applications, however, have been misused in the past. All neuroscientists share the responsibility for limiting the use of brain-stimulation techniques in human beings to therapeutic purposes, and for guarding against the unwarranted or unethical applications of those techniques. Yet neuroscientists must also be prepared to communicate the positive character of their work in a society suspicious of "mind control." The potential value to society of applying such knowledge to physiological disorders of personality and mental function calls both for continued basic research and for efforts to build bridges to the clinic.

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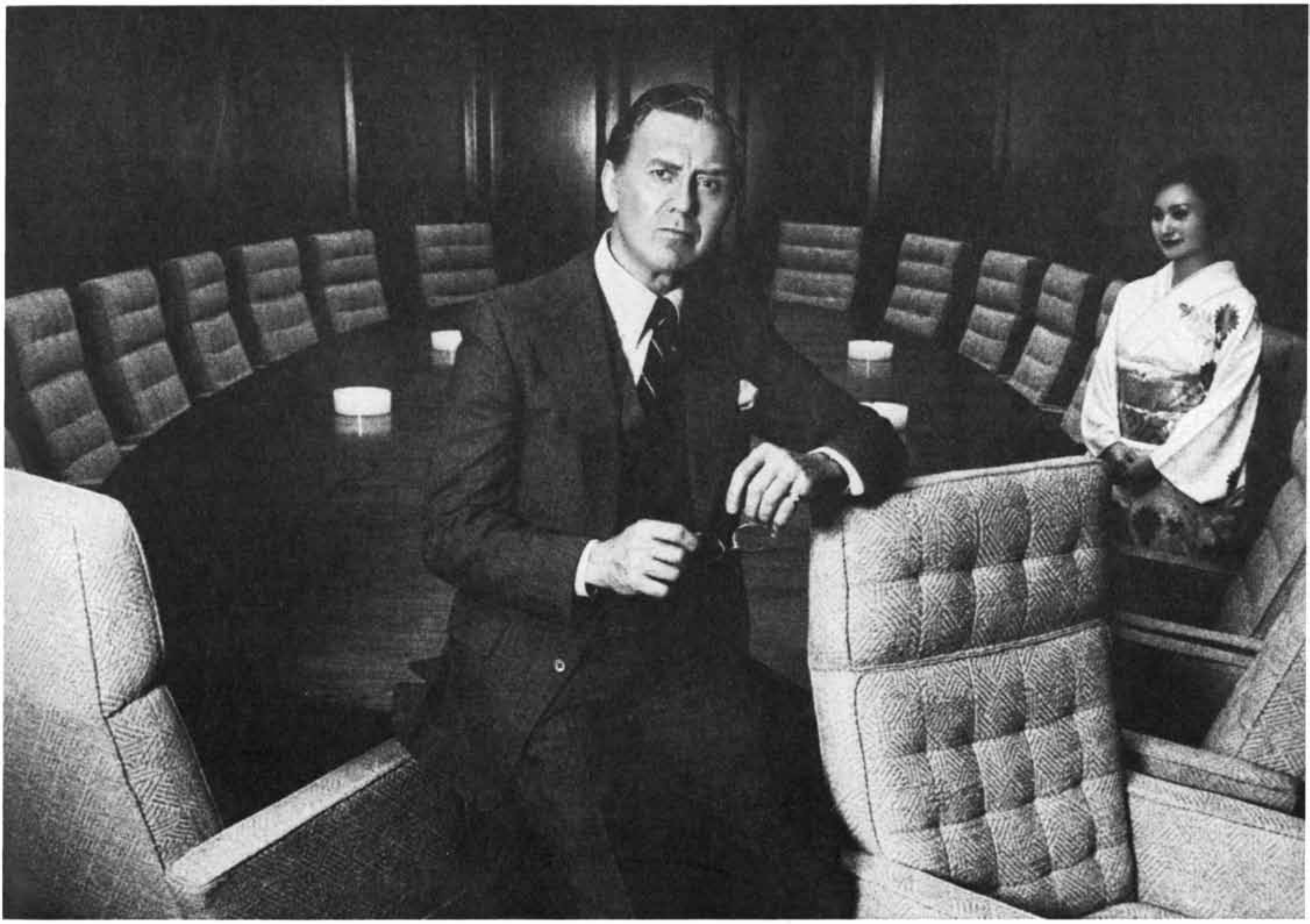

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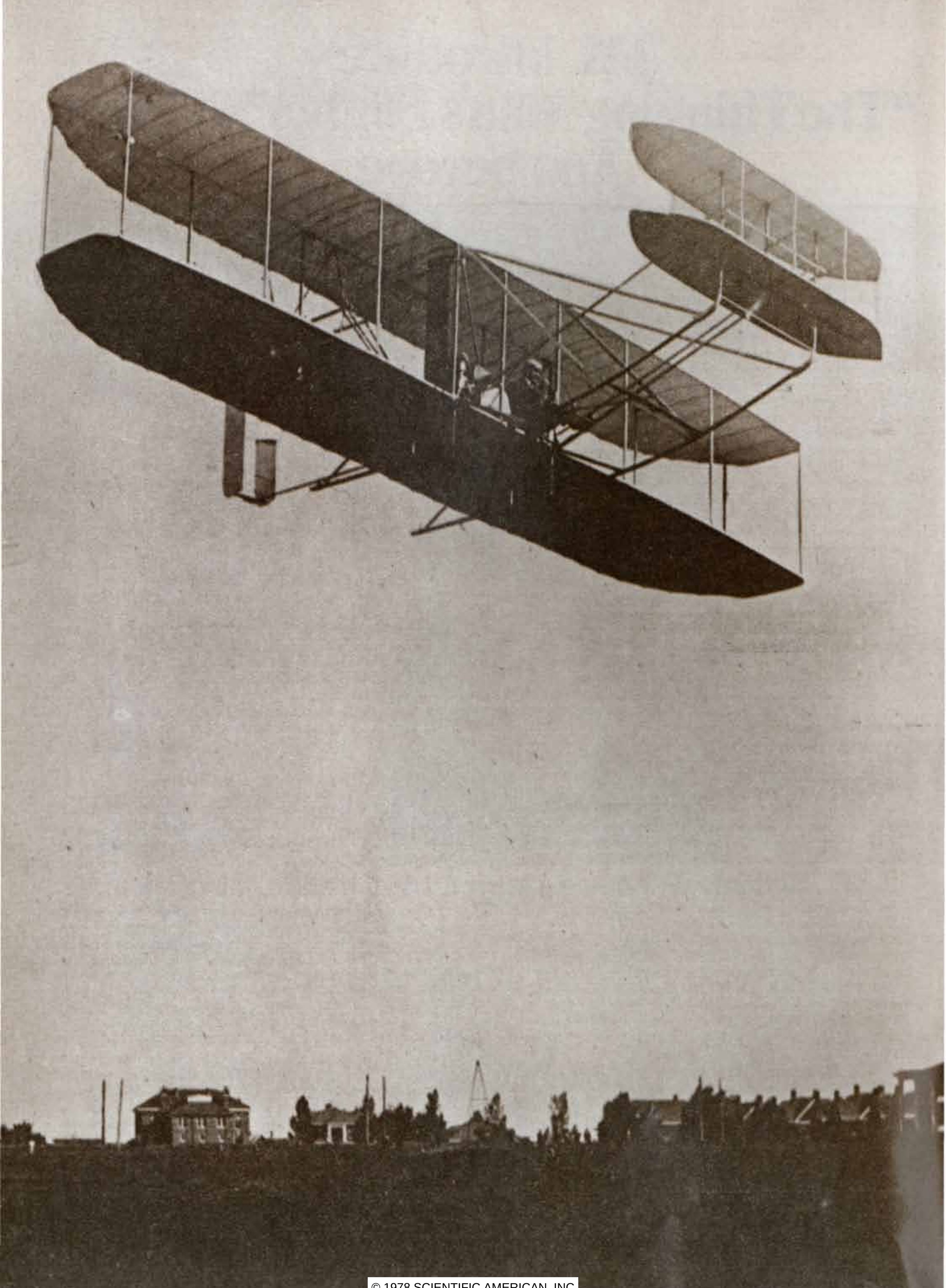


The Wright Brothers' Flight-Control System

The Wrights' gliders and powered "Flyers" had an elevator in front instead of in the rear. The system has seemed inherently unstable, but it appears that the Wrights had good reasons for selecting it

by Frederick J. Hooven

Wilbur and Orville Wright invented the controllable airplane. Until they first flew in public in 1908 it was believed a powered aircraft would be similar in its behavior to an airship, a stable vehicle that could be steered right and left by a rudder and up and down by a horizontal rudder, or elevator. One could expect to mount such a craft and fly it without previously acquired skills, and that was what was invariably attempted until the Wrights showed how it should be done.

In contrast, the Wrights, who were builders of bicycles, conceived the airplane from the beginning as being a vehicle that like the bicycle depended on its operator not only for its direction but also for its equilibrium. It therefore seemed perfectly natural to them that before one could hope to successfully operate a powered aircraft one needed to develop both the aircraft and the skills necessary for operating it.

The dictionary definition of stability, as applied to aircraft, is: a characteristic of an aircraft in flight that causes it, if disturbed from its condition of equilibrium or steady flight, to return to that condition. There are degrees of stability, and although nearly all aircraft today have sufficient stability to recover their equilibrium after small disturbances, none has sufficient stability to ensure its equilibrium under all possible conditions. The aircraft must maintain its equilibrium with respect to the air, and a highly stable airplane requires still air in order to progress evenly; the highly stable airplane is the servant of the wind, not of its pilot. There are also degrees of instability. The bicycle is unstable, but the instability is such that it is readily overcome by the high degree of control the operator has over the machine's equilibrium. Once the operator has acquired the necessary skill, control becomes instinctive and equilibrium is not a problem. The Wrights' early aircraft were unstable, and it was not until 1905 that they achieved a powered machine with a low enough degree of instability combined with a high enough degree of control to enable them to learn the needed skills and accomplish their objective of practical controlled flight.

An aircraft's flight calls for three kinds of control, corresponding to its three axes of rotation: roll, yaw and pitch. Roll is rotation about the longitudinal horizontal axis; it determines the lateral attitude of the aircraft (left wing up or right wing up). Before the Wrights there was no concept of lateral control. It had been found in the flying of models that giving the wings a dihedral angle, that is, raising the wing tips above the wing roots, would provide sufficient stability to maintain equilibrium about the longitudinal horizontal axis in straightaway flight. The Wrights, who were careful students of soaring birds, noticed that although some birds (pigeons and turkey vultures, for example) use the dihedral, many do not, and that all soaring birds make subtle changes in the configuration of their wings to control their lateral equilibrium.

The Wrights therefore were the first to conceive the idea of increasing the lift on one side of the aircraft while simultaneously decreasing it on the other as a means of accomplishing lateral control. They finally had the idea of twisting the wings so that one wing presented itself to the wind at a greater angle than the other one. Today this is accomplished by ailerons, small flaps along the trailing edge of the wing that modify its lift characteristics to achieve the same end.

Changes in yaw, that is, rotation about the vertical axis, determine the direction of the flight path to the left or the right. Yaw control is effected by a rudder, a vertical control surface placed at the rear of the machine by the Wrights as it had been in all other floating or flying craft. Bicyclists are accustomed to "banking" as they round a corner, which is of course accomplished by the lateral control; thus the lateral and yaw controls are closely interrelated. Working out this interrelation was one of the Wrights' triumphs in achieving control and learning to fly.

Pitch, or nose-up, nose-down, control stands alone and can be regarded as being substantially independent of the other two controls. Pitch control presented unexpected problems to the Wrights that did not materialize until they had built and flown powered aircraft, and it was the solution of these problems that occupied much of the two-year period between the first powered flight in 1903 and the final achievement of practical flight two years later. Pitch control is accomplished by the elevator, or stabilizer, which is normally placed behind the wings but which was placed in front of the wings by the Wrights in all their aircraft built before 1910.

An aircraft is balanced by distributing its weight along its longitudinal axis so that its center of gravity coincides as nearly as possible with the center of lift of the wing. In this way the machine is balanced on its center of gravity much as the beam of a scale is balanced on its fulcrum. In flight, however, the weight shifts, as when passengers move about or fuel tanks are emptied, and some auxiliary means is obviously needed to lift up or push down on the nose or the tail of the machine to balance it. An-

TYPE "A" WRIGHT FLYER, the model demonstrated in the U.S. and abroad in 1908, is seen in the photograph on the opposite page. Orville Wright is piloting the machine above the parade ground at Fort Myer, Va., during a demonstration for the Department of War on September 9, 1908. In France that month Wilbur Wright established world altitude and endurance records.

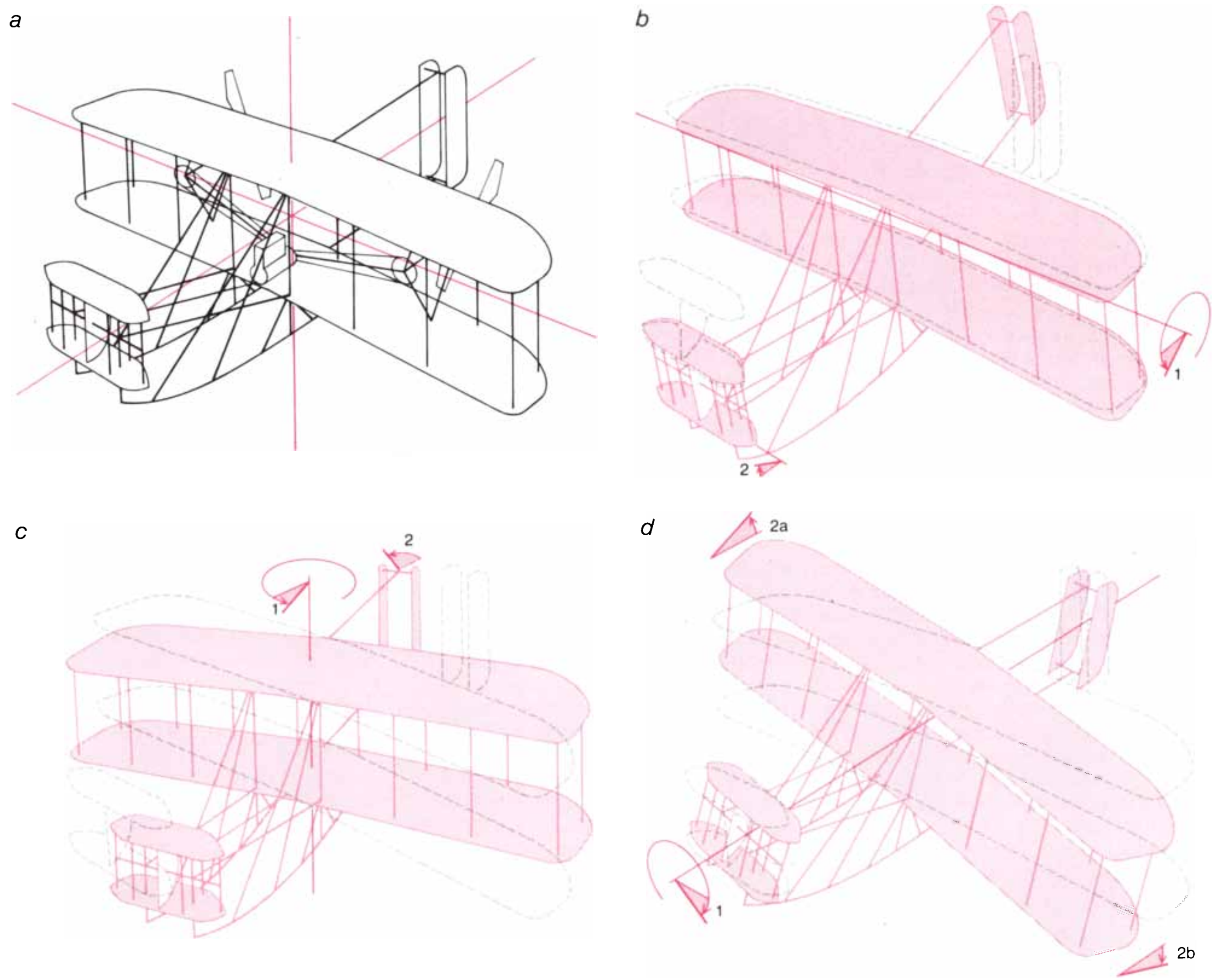
other disturbing influence is the fact that the fulcrum, the wing's center of lift, moves with changes of the plane's flight attitude.

When the Wrights began their work, existing data indicated that the movement of the center of lift was such as to cause the machine to be stable in flight. What this means is that any change of attitude from equilibrium would be such as to induce a change of attitude tending to restore the original equilibrium. If the plane were to be caused to assume a more nose-up attitude, and if that change of attitude were to result in a rearward movement of the center of lift, the machine would be stable, since such a movement would cause the nose of the machine to drop. What the Wrights found instead was that when the wing was cambered, the center of lift over much of the range of attitudes was in the opposite direction, causing the machine to be unstable. Hence the operator was required not only to use the elevator to effect changes in the plane's attitude and direction but also to manipulate it in a constant balancing act to maintain its attitude, just as the rider of a bicycle uses the handlebars both for direction control and for balancing the machine.

In their first man-carrying glider, flown in 1900, the Wrights discovered they could overcome this instability by placing the elevator to the rear of the wings, which they did simply by flying the glider backward. Yet they decided to keep the elevator in its forward position in spite of the instability. Being bicycle riders, they found the instability was no problem. They persisted in this practice not only with all their gliders but also with their powered machines built before 1910, when they adopted the conventional rear elevator for the first planes they manufactured in quantity.

The front-elevator configuration later came to be known as the canard, because of its fancied resemblance to a duck. It has been generally shunned by aircraft designers as unstable, and the Wrights have been criticized by historians for persisting in its use on their powered machines. Why did they do it? To answer the question it is necessary to go back to the beginning of the Wrights' interest in manned flight.

Before the Wrights the only heavier-than-air flights had been made by hang-glider pilots, of whom the first and greatest was Otto Lilienthal. He was a successful German engineer for whom the Wrights had great admiration, and he was the compiler of the best aerodynamic tables before those of the Wrights. Lilienthal was killed in 1896 when a gust of wind caused his machine



MOTION AROUND THREE AXES must be controlled in flight. At *a* the three axes (pitch, yaw and roll) are seen. At *b* motion around the pitch axis, nosing down (*1*), is seen; equilibrium is restored by moving elevator to a nose-up position (*2*). At *c* motion around the yaw axis, a turn to the left (*1*), is seen; equilibrium is restored by moving the rudders to a right-turn position (*2*). At *d* motion around the roll axis, lowering the left wings (*1*), is seen; the Wrights restored equilibrium by warping the wings (*2a, 2b*) into a left-wing-up position.

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to lose flying speed and plunge to the ground. This loss of flying speed is what is known today as a stall. It is almost always followed by a dive, and if the aircraft has enough altitude, the dive enables it to regain flying speed. Since a hang glider is normally flown at low altitude, there is seldom room for such a maneuver.

The news of Lilienthal's death attracted the attention of the Wrights, and soon afterward they began to think about gliding as a sport. From the beginning they thought about making their glider controllable by changing the angle of the elevator. They decided to put the elevator in front of the wing in the belief that it would prevent the dive following the stall. Lilienthal and his followers had put fixed elevators at the rear of their machines, and what control they had was achieved by the operator's shifting his weight. This provided little control over the machine's attitude and almost none over its direction; it simply went where the wind took it.

In 1899 the Wrights built a biplane kite with a five-foot wingspread that embodied their wing-twisting roll control. They found it responded to their control. They then proceeded to plan their 1900 machine and to search for a place where there would be winds steady enough for them to fly it as a kite and sandy hills for them to glide and land it without damage. They settled on the sand dunes near Kitty Hawk, N.C.

The Wrights' first machine had no rudder. It depended on the tilting of the wings to the right or left in the expectation that it would turn in the direction in which it was tilted, much as the experience of the hang-glider pilots had been. Its control system achieved an important improvement over the hang gliders in that the operator, no longer being required to shift his weight for control, was able to lie prone on the lower wing, thereby greatly reducing the head resistance of his body. The Wrights also realized that their control system would work on machines that were much too heavy to be controlled by the operator's shifting his weight: machines that would be powered.

They first flew their glider as a kite, carefully measuring the forces of lift and drag while they measured the velocity of the wind with a hand-held anemometer. Their meticulous calibration of the anemometer and their painstaking measurements of the angles of the ropes that held the machine eventually enabled them to make fundamental corrections in the aerodynamic data then available. From the beginning they began to doubt the accuracy of Lilienthal's tables, which they applied to the design of their 1900 and 1901 gliders.

The Wrights also flew the machine as a glider, experimenting by rigging it with a dihedral angle. They discovered

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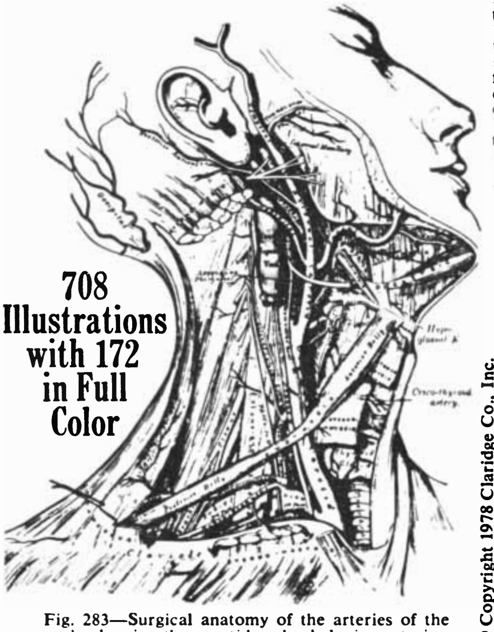

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Fig. 283—Surgical anatomy of the arteries of the neck, showing the carotid and subclavian arteries.

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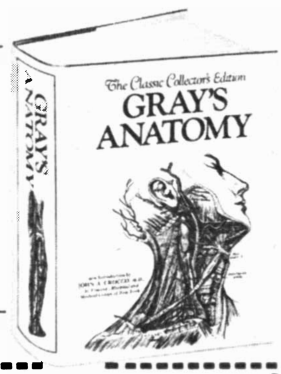

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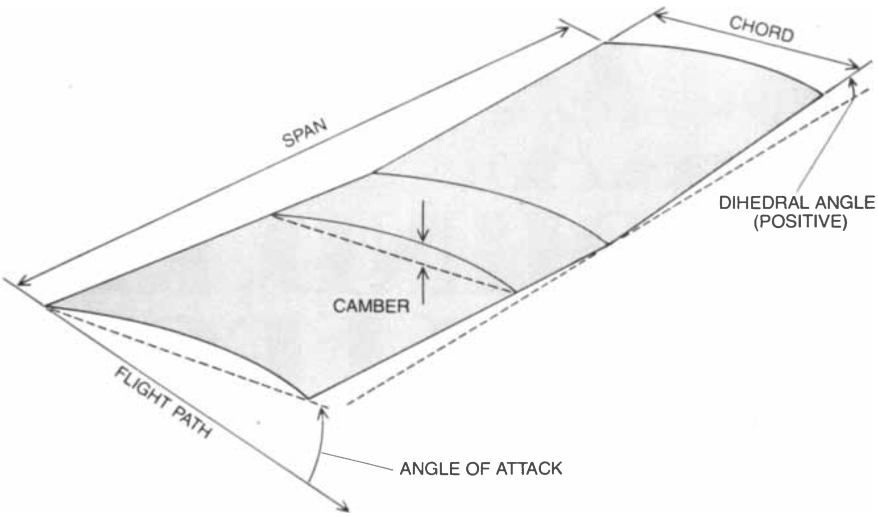


AIRFOIL TERMINOLOGY is defined in this diagram of a stylized glider wing of the 1900's. Wingspan is the total distance from wing tip to wing tip; chord is the distance from the leading edge to the trailing one. Multiplying the chord by the span yields the total airfoil area. The aspect ratio of the wing is the ratio of the span to the chord. A long, narrow wing has a high aspect ratio and a short, wide wing has a low one. If the wing consists of two planes, the angle formed where they meet is a dihedron; in this example the dihedral angle is positive. A wing with a curved cross section, as seen here, is said to be cambered. The angle at which the wing is inclined to the direction of motion is the angle of attack; if too steep, loss of lift causes a stall.

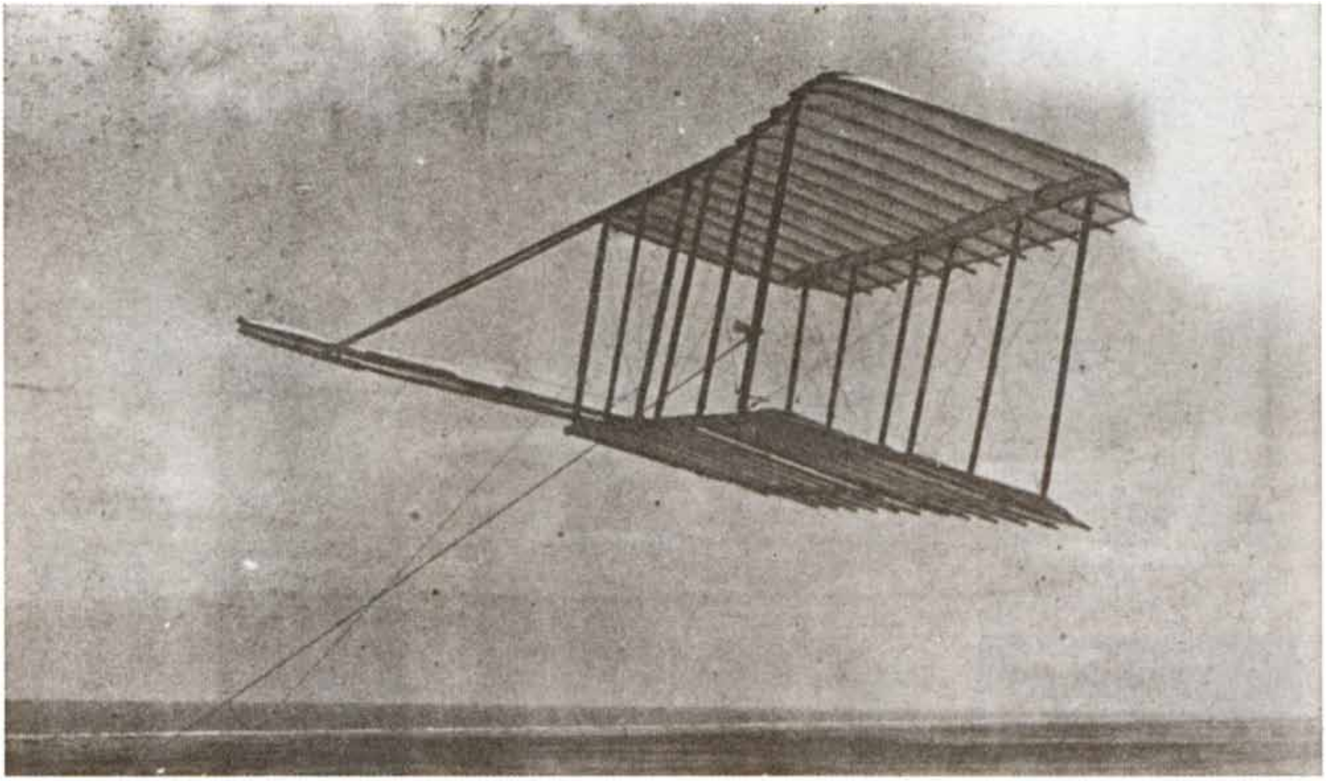
that this caused it to react to every cross wind, thus interfering with the operator's choice of direction. It was this machine they flew backward with the elevator at the rear, learning that such a system increased stability. Since they valued freedom from dives more than stability, however, they left the elevator in the front.

It was a good start. Their control system had worked well, their plan of flying the machine as a kite had worked out as they had planned, even though some of their data did not agree with existing tables, and their brief experience at gliding had been both promising and fun. They began at once to plan a new and larger glider for 1901. It had 290 square feet of wing area (as compared with 165) and more deeply cambered wings. It proved to be a disappointment. It was so unstable that it was difficult to control, and it had a steeper glide angle than the 1900 glider.

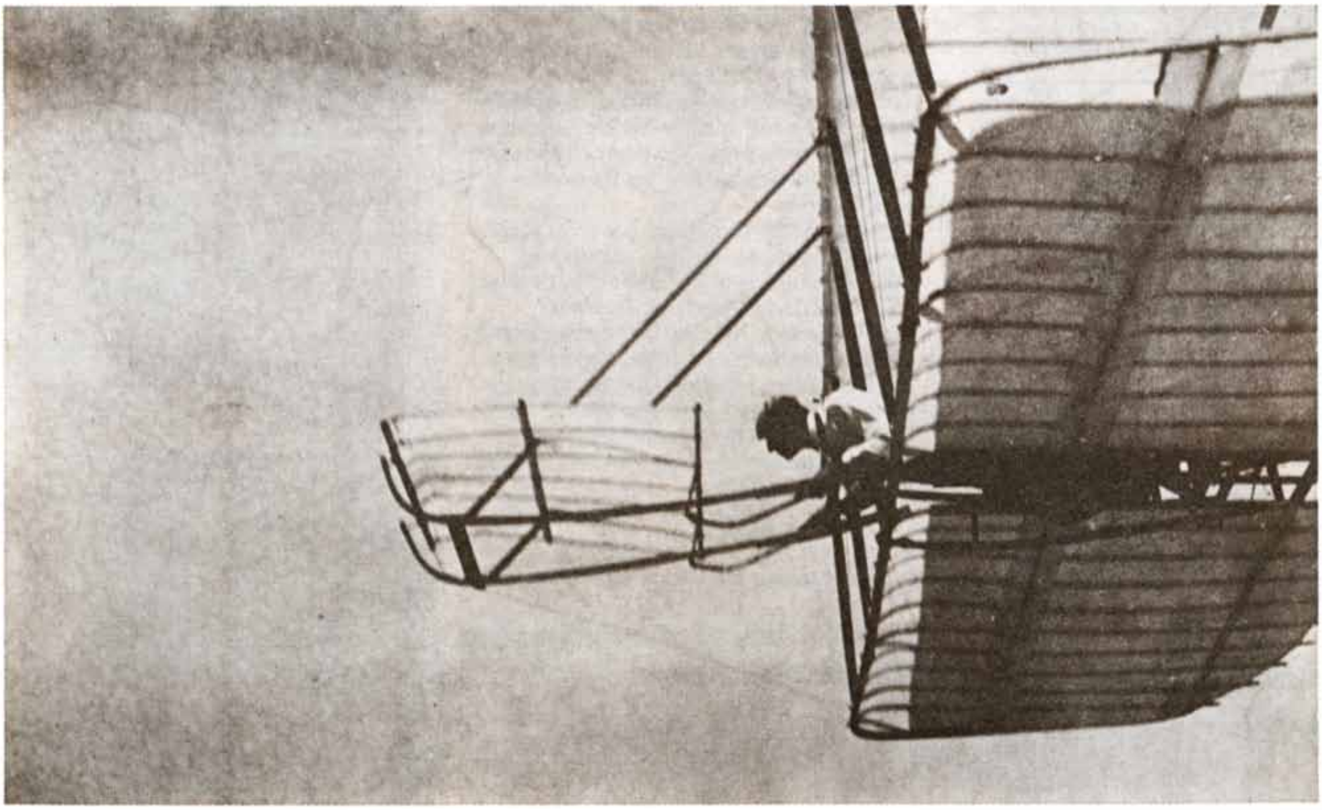
The Wrights rebuilt the wings to reduce their camber, and they modified the wing to improve the streamlining of its leading edge. These changes completely solved the problem of stability and improved the glide angle. The shape of the wing section after the modification can be seen clearly in a photograph of the glider in flight [*see bottom illustration on page 174*]. The reverse curvature visible in the rear half of the wing profile is characteristic of the sections designed to avoid the unstable movement of the center of lift of cambered wings. From this it can be inferred that the 1901 machine was actually stable, a conclusion that is confirmed by a note entered in the diary of E. C. Huffaker, a visitor to the Wrights' camp in 1901. He watched the Wrights make several flights in the machine with its elevator fixed.

The Wrights did a great deal of flying in this glider, and it provided them with two particular sources of satisfaction. Their lateral control system performed well. They had twice found themselves in the same kind of stall that had killed Lilienthal, and instead of diving their machine had just settled to the ground. This confirmed the wisdom of their choice of the front elevator.

The 1901 machine also convinced them that since the Lilienthal tables of aerodynamics were seriously wrong, they would have to make their own measurements if they were going to build a successful powered machine. Once back home in Dayton, Ohio, they proceeded with measurements of the aerodynamic characteristics of more than 60 model wings of various cambers, shapes, aspect ratios and thicknesses, singly and in biplane form. In these studies they worked with a small wind tunnel of their own devising. With much wisdom they decided not to try to measure the minute forces on their models. Instead they measured the ratio between two wind forces within the airstream by finding the direction of the resultant of the two forces. For this purpose they used two different parallelogram linkages ingeniously contrived of bicycle spokes. One linkage measured the lift on the model wing by comparing it with the resistance of a flat plane at right angles to the airstream. The other linkage measured the drag by comparing it with the lift. The forces on a full-sized wing could then be



GLIDER OF 1900, seen in flight as a kite in this photograph, had only two controls: wing-warping to maintain equilibrium around the roll axis, and a forward elevator-stabilizer, barely visible at this angle, to maintain equilibrium around the pitch axis. The wings have been rigged to assume a slightly negative dihedral angle. As this near-profile view shows, the wings were constructed with little camber.



GLIDER OF 1901, seen in this photograph with Wilbur Wright as the pilot, also had only two controls: wing-warping for roll-axis control and a movable forward elevator-stabilizer for pitch-axis control. The elevator's single surface had a low aspect ratio. The 1901 wings were at first constructed with more camber than the 1900 wings but were later flattened, as is visible here, in order to improve stability.

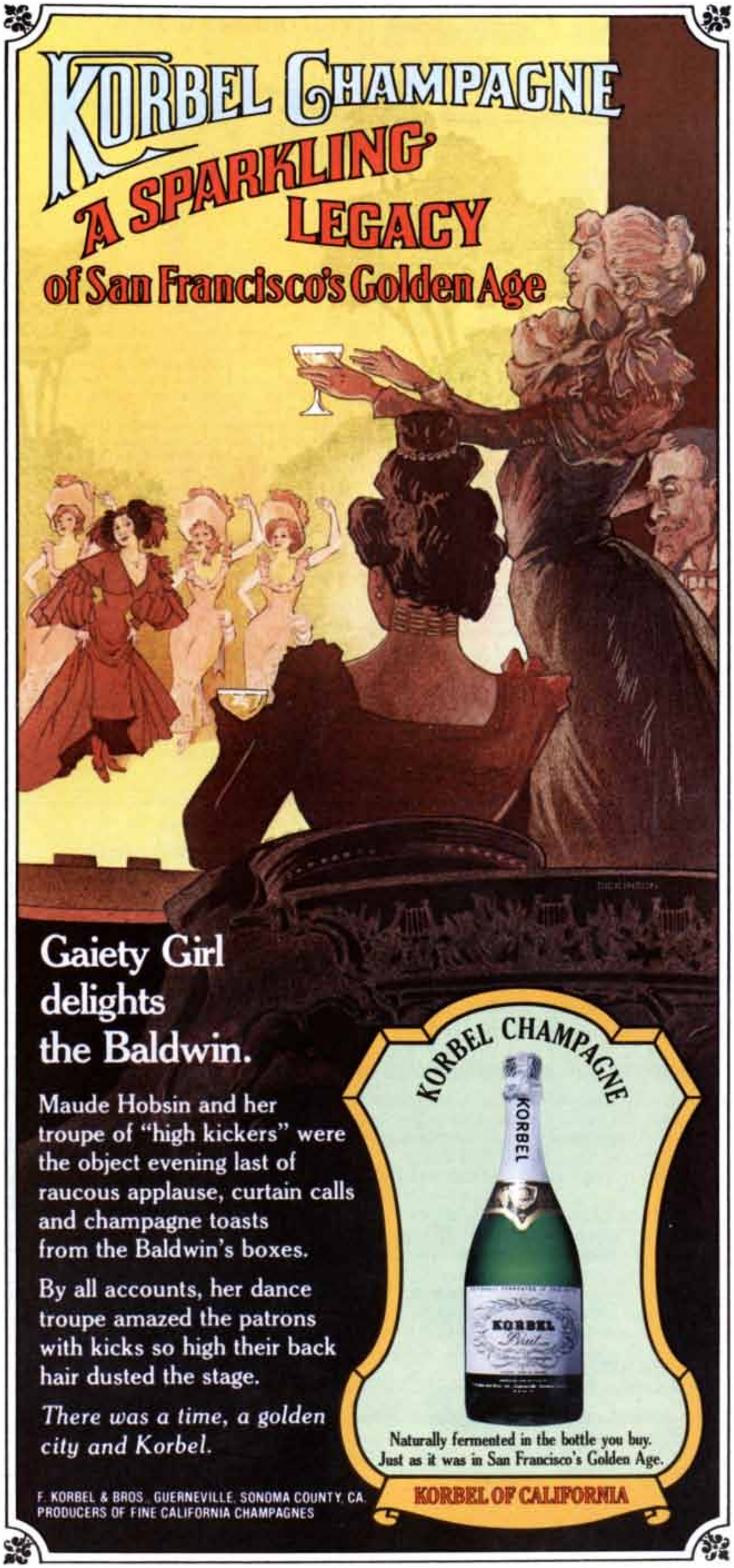
predicted by comparing them with the force on a full-sized flat plane measured by the Wrights' meticulous procedures in the steady wind of Kitty Hawk. In this way they avoided the worst pitfalls of model testing on a small scale: the difficulty of measuring small and probably unsteady forces and effects of scale that result from the viscosity of the air (which the Wrights probably were not even aware of).

Working with their own tables this time, the Wrights designed the 1902 glider. It was still larger, with a 32-foot wingspan instead of the 22-foot one of the 1901 machine but with a wing chord of only five feet instead of the seven feet of the earlier machine. It weighed more than 100 pounds. Nothing that large had ever flown before. The wing area, 320 square feet against the 290 of the 1901 glider, was not much greater, but the increased aspect ratio, with a span of 6.4 times the chord, provided considerably more lift. For the first time the machine included a pair of fixed vertical surfaces behind the wings to stabilize motion about the yaw axis.

This glider was a success from the start, and the Wrights soon broke all records for endurance and flatness of glide path. The vertical fin in the rear proved to be an advance over previous gliders in its development of the complex interaction of yaw and lateral controls in turning. The Wrights had found that their method of turning by tilting up one side of the machine did not work as they had expected. For example, to make a left turn they would raise the right wing, but then instead of turning to the left the machine would exhibit a tendency to turn to the right, because the right wing, having the greatest lift, would also have the greatest drag, and that would keep the right wing from moving ahead as expected. Being thus banked for a turn without making the turn, the machine would simply move sideways downward to the left, and the flight would end as the machine hit the ground.

The fixed rear fin had tended to correct this condition by causing the machine to turn in the direction of the sideslip. The correction, however, was too little and too late, and in the middle of the season the Wrights conceived the idea of converting the fixed fin into a rudder that would turn as they warped the wings, helping to get the turn started. In this change the double surface became a single one. At that point the Wrights had in place for the first time all the control surfaces needed for complete three-axis control. This arrangement lasted until the middle of the 1905 season, when they at last separated the rudder control from the wing warping and had the three independent controls all aircraft have had since.

After the 1902 season the Wrights



knew they were ready to build a powered machine. They designed their 1903 "Flyer" along the same general lines as the 1902 glider, with a 40-foot span and a 6.5-foot chord, having 510 square feet of wing area to carry the extra weight of the power plant and the propulsion system. After vainly seeking an engine from automobile manufacturers they designed and built their own four-cylinder in-line horizontal engine. It weighed some 200 pounds with the necessary fuel and cooling auxiliaries and developed 12 to 13 horsepower.

In some ways the development of the Flyer's propellers was the most remarkable of all the Wrights' accomplishments. They developed a theoretical analysis of the screw propeller for the first time, and they produced the first efficient air propellers that had ever been made. How they did it is a secret of the unrecorded dialogue between the two brothers, but the figures are there. These propellers were about 70 percent efficient, a figure that would do credit to a modern designer under the same circumstances. They were pushers, large (eight feet across), slow-turning (380 revolutions per minute) and driven in opposite directions of rotation by bicycle chains. They thus canceled any twisting reactions that might have complicated lateral control.

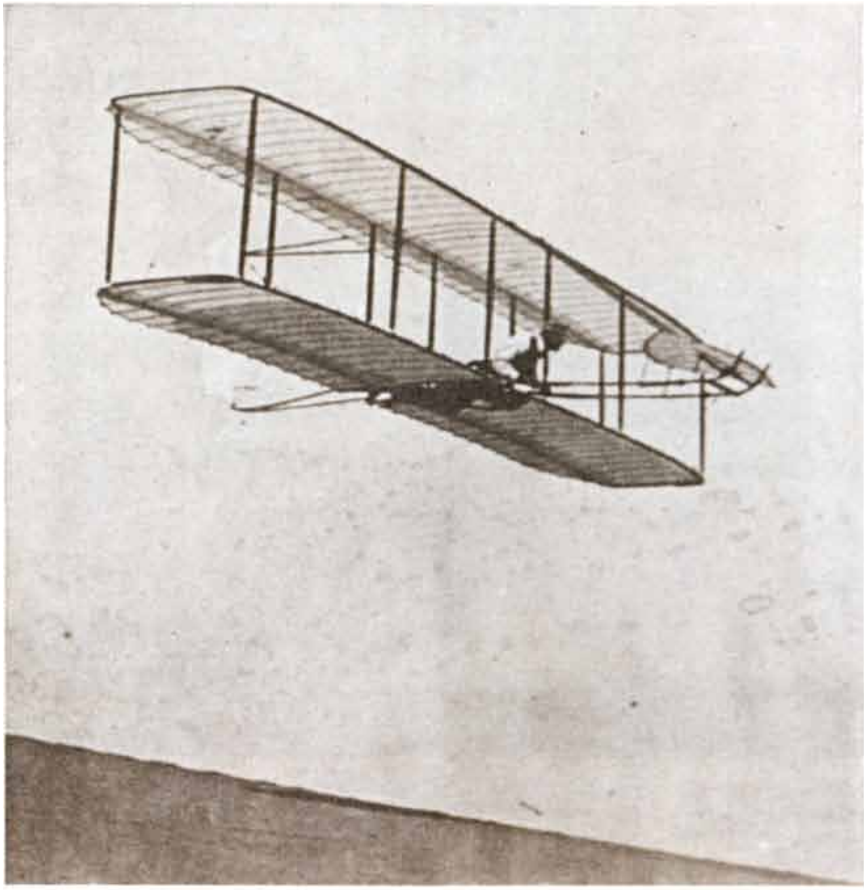
While the Wrights were assembling the 1903 Flyer at Kitty Hawk in the fall of that year they took time off to make many flights in the 1902 glider. They became skilled at soaring, and before the end of the season both brothers had exceeded one minute in flight: Orville soared for $71\frac{3}{4}$ seconds and Wilbur for $69\frac{1}{4}$ seconds. These were new records for duration of flight.

After a series of disheartening troubles with the propulsion system the Flyer was ready on December 14. Wilbur, who had won the toss, was the pilot. The new machine proved to be unexpectedly hard to control in pitch. Immediately after takeoff it darted into the ground, breaking the elevator and ending flying for that day.

Determined to get home for Christmas, the Wrights launched the Flyer again on December 17, in spite of a gusty wind of more than 20 miles per hour, this time with Orville at the controls. The machine was unstable, tending to dart up and down, a condition that was aggravated by the wind gusts and by an elevator that tended to go to the extremes of its travel. Having to accustom himself to new and difficult controls in the face of a gusty wind, Orville did well to remain in the air for 12 seconds, during which time he covered only 120 feet. Each brother made two flights that day, and on the last flight Wilbur stayed in the air for 59 seconds, covering 852 feet. This flight was terminated by a downward plunge that once again damaged

Which Borkum Riff?

For all of the flavor and none of the bite...Borkum Riff.



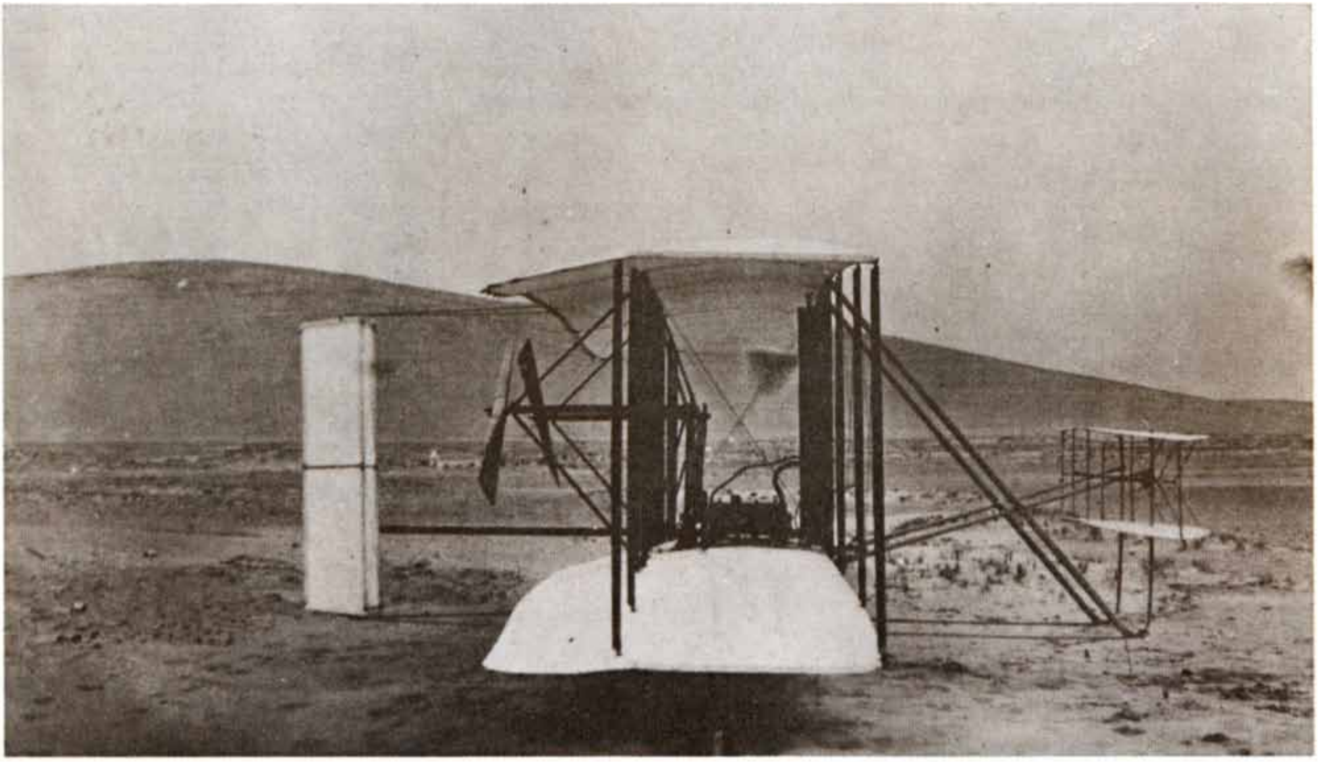
GLIDER OF 1902, with Wilbur Wright again as pilot, had a three-axis control system: wing-warping for roll control, single elevator (of higher aspect ratio and set farther forward) for pitch control and a single vertical rudder for yaw control. The Wrights first placed a fixed rudder well to the rear of the wings. The movable rudder was installed in place of the fixed rudder at Kitty Hawk to improve control over the interacting roll-axis and yaw-axis motions. The Wrights now for the first time had attained potential control over all three flight motions.

the front elevator frame and ended the day's flying. As the brothers were standing by the Flyer discussing the flights the wind overturned the machine and wrecked it. It never flew again.

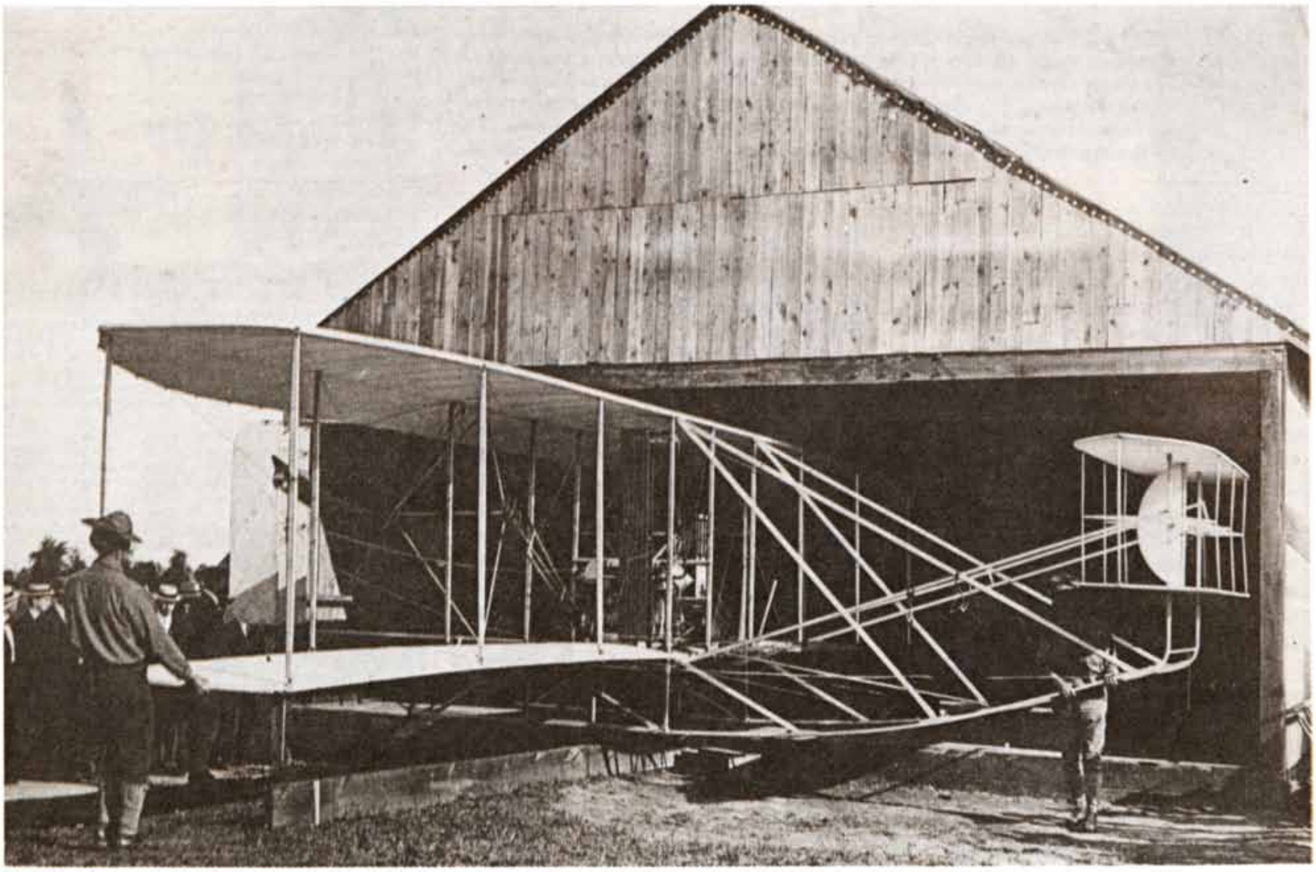
With power the Wrights no longer needed Kitty Hawk, and in 1904 they arranged to fly their machine on the farm of their friend Torrence Huffman, near their home in Dayton. They began building two new machines that spring, both substantially duplicates of the 1903 Flyer. One of these became the 1904 Flyer and the other the 1905. They also built a new and more powerful engine, which developed 16 horsepower at the start of the 1904 season. Its power increased as it became better broken in, and at the end of the 1905 season, running at a somewhat higher speed, it developed 20 horsepower.

The limited area of the Huffman farm required that the Wrights make sharper turns than they had been making in the gliders at Kitty Hawk, and this proved to be a problem. They finally learned to juggle the controls so that they could make circles within a rather small field, but now a new difficulty appeared that puzzled them. Every so often the machine would lose control and simply sideslip into the ground. This condition, which I shall call a stall turn, was still a puzzle at the end of the 1904 season.

The machine also shared its predecessor's tendency to "undulate," as Wilbur put it, in pitch attitude. In July, 1904, it was rebuilt. The engine, the fuel tanks and the radiator were moved so that the center of gravity was shifted to the rear by three inches. Now, however, the machine was so much more unstable that it was practically unflyable. Rather than rebuild it again to move its center of gravity forward, the Wrights ballasted it with 70 pounds of iron on the front elevator frame, bringing the center of gravity forward by eight inches, or five inches ahead of where it had been. Although the machine still undulated, it was more flyable. It finished the season in this condition and was then scrapped, with the engine and propulsion system being saved.



FLYER OF 1903, the Wrights' first powered machine, is seen in profile after its final assembly at Kitty Hawk. The single forward elevator of the 1902 glider has been replaced by a double elevator and the single rudder by a double rudder. The wing area was enlarged to accommodate the weight of the machine's engine, cooling system and propellers. Note that the wings are rigged for negative dihedral.



FLYER OF 1908, the Wrights' Type A, is seen undergoing inspection by officials of the Department of War. The demilunar vertical surface between the elevators is one of twin "blinkers" the Wrights first added to their 1905 Flyer to improve yaw-axis equilibrium. Both the forward elevator and the rear rudder were set farther from the wings than in 1903–4; the change greatly improved controllability.

The 1905 Flyer began its life almost exactly like the 1904 model except for the addition of "blinkers," small vertical surfaces placed on the elevator frames to decrease the tendency of the machine to turn into a sideslip or a cross wind. It flew much as its predecessor had, having the same tendency to undulate. Its instability resulted in a crash in July, from which Orville emerged miraculously unharmed. After that it was rebuilt with a larger elevator at a greater distance from the wings, more than doubling its control effectiveness. Meanwhile the drooping wings of the 1903 machine had proved unnecessary on the powered machines, and they had disappeared by early in 1904. The 1905 machine was rigged with a slight dihedral, providing for the first time a small degree of lateral stability. As the season progressed the rudder was enlarged and was moved farther outward, and finally it was made independent of the lateral control. The machine was ballasted with 28 pounds of iron to bring the center of gravity forward another four inches.

With the changed elevator the real flying began, and with more flying experience the Wrights found that their stall turn problem could be solved by simply putting the Flyer's nose down to gather a little additional speed for the turn; they realized that the centrifugal force, added to the plane's weight, required more speed and power than straight flying. The final flights increased in length, the longest of them lasting for 38 minutes and covering 24 miles. This one flight of October, 1905, represented more flying time than the total of the 104 flights of the 1904 Flyer. The Wrights now knew they were ready to put their machine on the market. The 1905 Flyer was the culmination of their development of aircraft control. It was the world's first practical airplane, and it had flown routinely before anyone else's heavier-than-air machine had even left the ground.

The Wrights did not fly again until 1908. They spent the intervening time on finding a market for their machine, developing a new and more powerful engine of about 30 horsepower and building a number of new machines basically the same as the 1905 model. In 1908 they put a new engine in the 1905 design and made the world's first flights with two people. For the first time they were seated on the lower wing instead of lying prone. Thereafter they went on to their well-known triumphs of 1908 in France and in Washington. They never did, however, progress beyond their 1905 model, and by 1910 their competitors had caught up with them.

We are left with several questions about the Wrights' pitch-control system. Why did they persist in mounting the canard elevator on the powered Flyers? Were they still concerned about the stall dive or did they just not want to change horses in the middle of the stream? Why did they have so much more trouble with the Flyers' pitch stability and control than they had had with the gliders? Why did they make the highly uncharacteristic blunder of moving the center of gravity of the 1904 machine to the rear when it should have been moved forward?

In seeking answers to these questions I found that no study had ever been made of the pitch stability and control characteristics of the canard-type Flyers. At the Thayer School of Engineering of Dartmouth College I have made such a study, determining the Flyers' static stability from existing aerodynamic data, from the Wrights' own notebooks and from measurements of the still-existing 1905 Flyer. I then explored the machines' dynamic stability by simulating their flight on a computer.

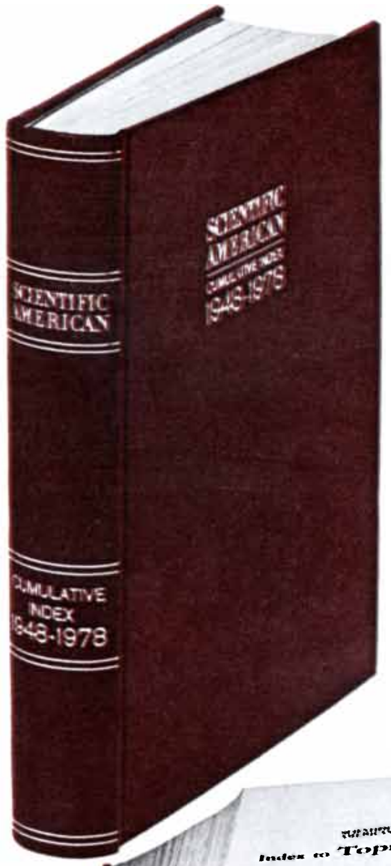
I have found that the Flyers were indeed unstable as they were flown but that their instability decreases as the center of gravity is moved forward. Each machine has a certain position of the center of gravity that marks the dividing line between stability and instability, with a range of positions forward of the point for which stable flight is possible. As the center of gravity moves forward, more of the weight is carried by the elevator, and for the 1903 and 1904 machines with their small elevators there remains little usable margin of elevator lift for control purposes. Hence the stable flight range is only of academic interest.

The table below lists the position of the center of gravity of each version of all the canard Flyers, including the single small-wing machine built in 1909 for the Army Signal Corps. It also lists the position of the boundary line between stability and instability. It can be seen from the table that the Wrights gradually approached pitch stability as their machines evolved, until they finally reached the point at which instability is readily overcome by control. Then they went no further.

In reconstructing the flight of the ma-

FLYER	LOADED WEIGHT (POUNDS)	CENTER OF GRAVITY (PERCENT OF CHORD)	STABILITY THRESHOLD (PERCENT OF CHORD)	NOTES
1903	750	30.8	23	FOUR FLIGHTS ONLY
1904	830	31.2	23	
1904	830	35.0	23	REBUILT TO MOVE CENTER OF GRAVITY THREE INCHES TO REAR
1904	900	26.3	23	70-POUND BALLAST ADDED TO ELEVATOR FRAME
1905	830	31.9	23	
1905	897	18.8	8	REBUILT TO ENLARGE AND EXTEND ELEVATOR
1905	925	12.8	8	28-POUND BALLAST ADDED TO ELEVATOR FRAME
1908	1,046*	20.3	13	
1908	1,196**	18.3	13	
1909	885*	20.7	5	
1909	1,035**	18.6	5	
1909	903*	17	5	18-POUND BALLAST ADDED TO ELEVATOR FRAME
1909	1,053**	15.3	5	

SUCCESSIVE MODELS of the Wright Flyers showed variations in two criteria of pitch-axis stability. One criterion is the position of the center of gravity, here expressed as a percent of the chord, that is, the distance behind the leading edge. The other criterion is the threshold of stability, a function of the relative areas of elevator and wing multiplied by the distance between the two. This is also expressed as a percent of the chord. When the center of gravity is ahead of the stability threshold (a condition never achieved by the Wright Flyers), the aircraft will be stable over its normal range. When it is not ahead, instability is increased in proportion to the increased distance between the center of gravity and the stability threshold. The Wrights preferred controllability to stability, although they used ballast to narrow the gap. One asterisk indicates that one man was aboard the machine; two asterisks, that two men were aboard.



An advance announcement of the new SCIENTIFIC AMERICAN CUMULATIVE INDEX MAY 1948-JUNE 1978

This November the Editors of SCIENTIFIC AMERICAN will publish a Cumulative Index to the 362 issues of the magazine from May 1948 through June 1978. This new Index embraces all the issues published under the present editorial direction, recording 30 momentous years of intellectual history.

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Index to Topics
A rotated key word index that offers access to the subject matter of all articles and Science and the Citizen items (*see facing page*).

Index to Proper Names
The names of all persons mentioned in the articles or Science and the Citizen items and of places and institutions featured in a primary role.

Listing of Tables of Contents
A chronological listing of the contents of all 362 issues that permits ready identification, by titles and authors, of the articles cited in the two foregoing indexes.

Index to Authors
An alphabetical listing of all authors of articles.

Index to Titles
An alphabetical listing of all articles by the first key word in the title and by the other key words in the title.

Index to Book Reviews
A listing of the longer book reviews in three parts: authors of books reviewed, titles of the books and reviewers.

Index to Mathematical Games
A listing of the puzzles, games and diversions presented in this department since its inception in January 1957, under the editorship of Martin Gardner.

Index to The Amateur Scientist
A listing of the projects, experiments and demonstrations presented in this department from April 1952 through February 1976 under the editorship of the late C. L. Stong and from July 1977 through June 1978 under the editorship of Jearl Walker.

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How the Index to Topics provides direct access to subject matter of 362 issues of SCIENTIFIC AMERICAN...and how to use it.

The Index to Topics is a rotated key-word index. That is: The topics cited in a given article are entered together in a cluster:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

Each of these "key words" takes its turn as the first term in the cluster in its entry and re-entry down through the alphabet of the Index to Topics:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]
genetics, DNA, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]
molecular structure, DNA, genetics, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]
x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]

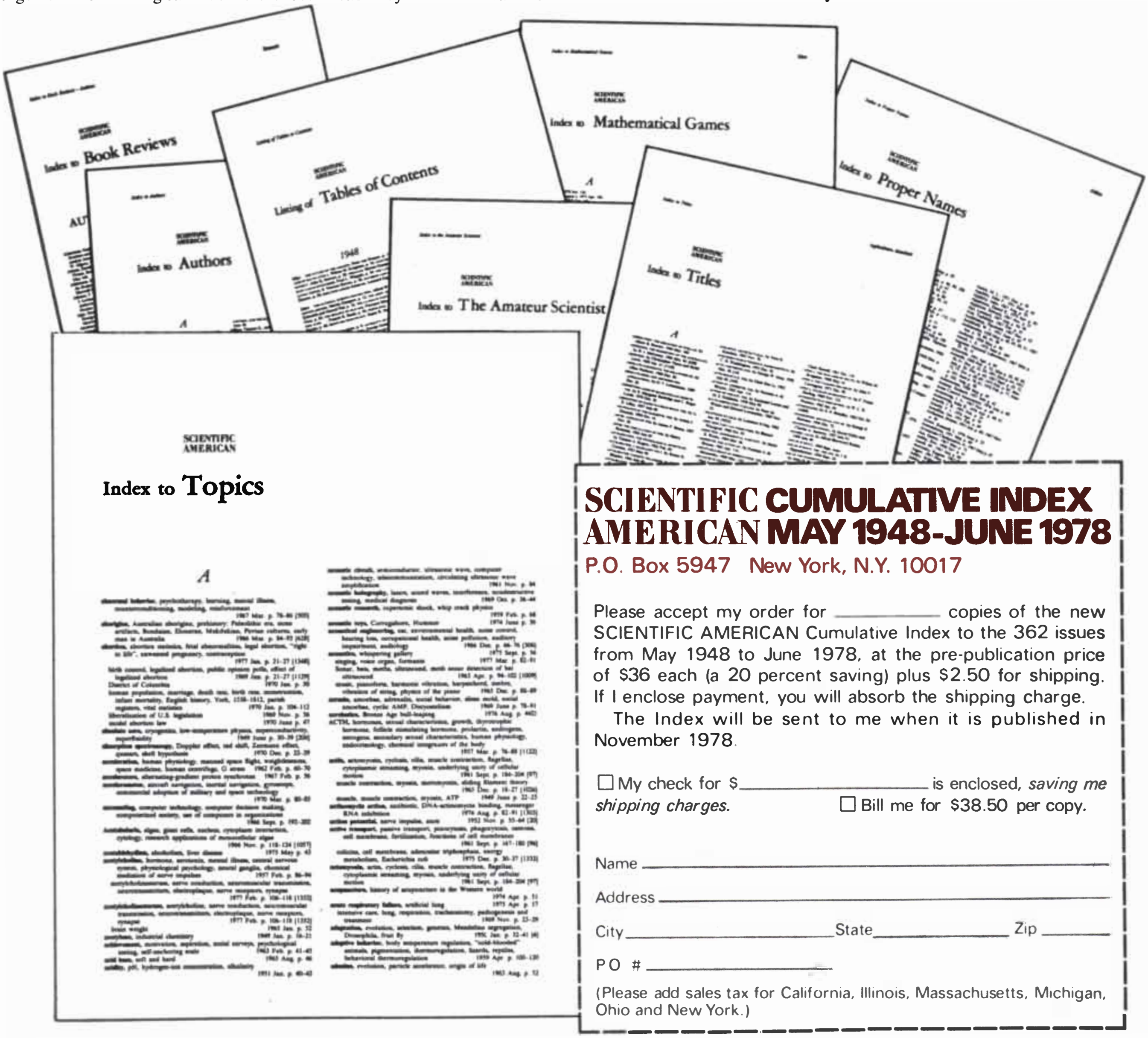
In most cases, a secondary citation, highlighting some aspect of the article, rides along with the rotating primary citations (In the example above: DNA double helix resolved). Each entry serves, therefore, as a "miniabstract" of the original. The alphabetical sequencing of the key words, in turn, brings together in chronological order references to each key word from various issues of the magazine. A portion of the grouping of clusters for "x-ray crystallography" follows:

x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]
amino acids, myoglobin, proteins, 3-D structure of protein molecule 1961 Dec. p. 96-110 [121]
crystal structure, solid state, semiconductors 1962 Dec. p. 39-48 [249]
Bragg's law, crystal structure, diffraction, fourier series 1968 July p. 58-70 [325]
photoelectric effect, x-ray absorption 1976 Apr. p. 96-103

Articles are referenced by first and last page numbers. Thus, the entry for x-ray crystallography informs the reader that first appearance of the term is in the October 1954 issue, pages 54-61. Reference to the Listing of Tables of Contents discloses that the article is "The Structure of the Hereditary Material" by F.H.C. Crick.

References to about one-third of the articles close with a bracketed number. This is the offprint number and identifies articles republished as offprints. Thus, the Crick article in the example is identified as Offprint #5.

Reference to the Index to Authors will disclose, as well, all of the articles written for SCIENTIFIC AMERICAN by F.H.C. Crick.



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MODERN AIRCRAFT with an elevator in front is the Swedish Viggen, a short-takeoff-and-landing aircraft with a speed above Mach 2. Such a configuration is known today as a canard.

chines I have simulated the 1905, 1908 and 1909 Flyers in their stable modes, with the center of gravity forward of its real-life position. The simulations show that it was quite feasible to fly the machines with stable and well-damped behavior with a fixed elevator. Indeed, the Flyers could have been taken off, flown and landed without touching the elevator control; the landing could have been accomplished by shutting off the engine and allowing the machine to glide to the ground. When the elevator is left free for conventional operation, however, the plane's behavior is flawed. Any attempt to fly it at a high angle of attack will result in what is known as a hammerhead stall, in which the elevator, operating at a higher angle of attack than the wing, stalls and drops, putting the machine into a dive not unlike that of a normal stall but having shorter duration and quicker recovery. This proves that if the canard is made stable by moving weight forward, it no longer serves to protect against the stall dive. Hence as long as the Wrights used the canard they were right in staying within the unstable range. I have further concluded that in view of the continual trouble they had with stall behavior in the 1903–5 development period they were wise to continue to use the canard, with its inherent protection against the stall dive. If it had not been for the forward elevator, the numerous stall turn episodes might have been fatal stall dives.

To simulate the flight of the machines in their unstable modes an automatic pilot has been programmed to perform the necessary balancing act with the elevator. The actual flights of the 1903 machine can be simulated with convincing realism by adding simulated random wind gusts to the flight program. I have been able to imagine myself in Orville's place as the machine bucks and darts in response to the gusts and as the elevator is manipulated to keep the machine as nearly level as possible. The simulated flights end when the machine darts into the ground, just as the prototype did in 1903, and the flights last anywhere from seven seconds to 70 seconds. The four actual flights lasted from $11\frac{1}{2}$ seconds to 59 seconds.

Why did the powered machines present such unexpected problems of pitch control? I have concluded that the Wrights were lulled by the relative stability of their gliders, forgetting the unstable behavior of the 1901 machine with its initial deep camber. The gliders all had a moderate camber, which decreased as the season went on and the single-strip wing ribs gradually straightened themselves out. The 1901 machine has been seen to have been positively stable because of the way the wing was flattened out in its rebuilding. The Flyers, on the other hand, had more deeply cambered wings, and they were heavier and faster than the gliders. They needed a firm hand and strong control, which they did not get until the final enlargement of the forward elevator of the 1905 Flyer.

Why did the Wrights make the blunder of moving the center of gravity of the 1904 machine to the rear? It is clear they were preoccupied with the complex roll-yaw problems and never gave the subject of pitch control the benefit of their keen analysis. I believe this was in part because they were lulled by the docile behavior of the gliders. As a matter of fact, it may be said that after 1903 the Wrights ceased to be keen analytical scientists and became busy builders. After their 1903 triumph there are no further examples of their fine analysis. They never recaptured their early scientific or innovative capabilities, and by 1912 they were clearly outstripped by their competitors. Wilbur died that year, and the marvelous symbiosis of the brothers died with him. It would have been the same if Orville had died. They had done enough.

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THE AMATEUR SCIENTIST

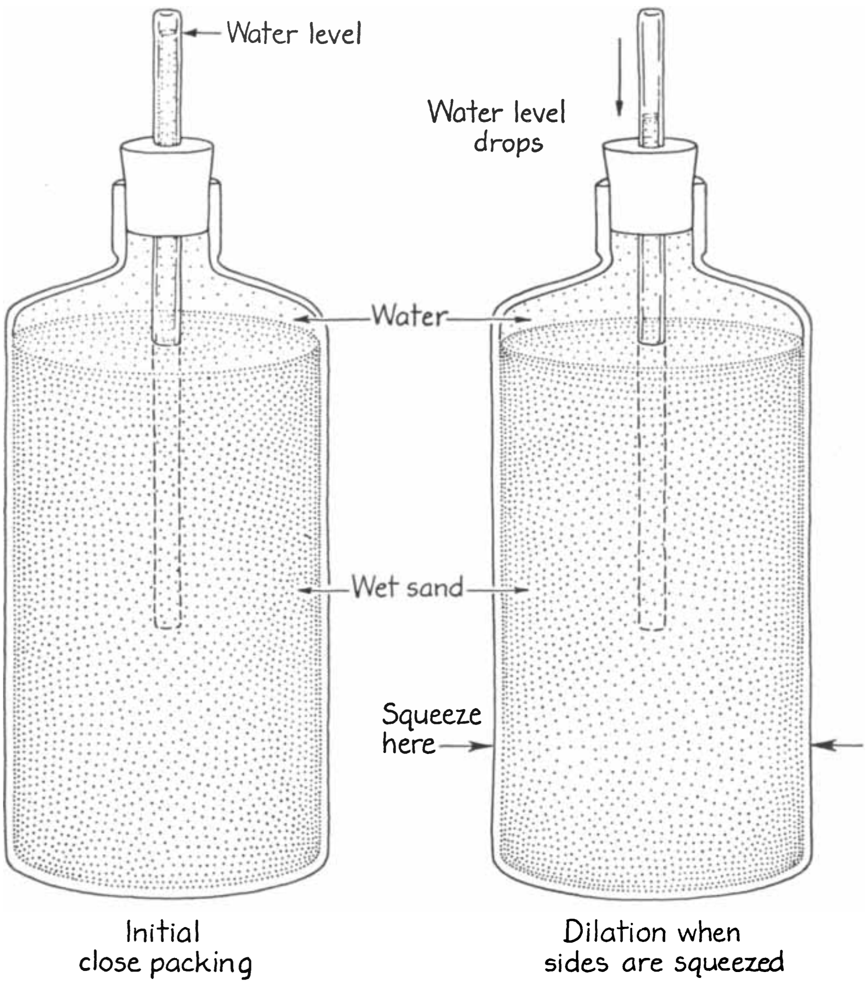
Serious fun with Polyox, Silly Putty, Slime and other non-Newtonian fluids

by Jearl Walker

Viscosity is the measurable resistance of a fluid to flow. The viscosity of water is fairly low; that of honey and syrup is considerably higher. With most common fluids the viscosity can be altered only by changing the temperature of the fluid. Viscosity is reduced by raising the temperature and increased by lowering it. Such fluids are called Newtonian.

In another class of fluids, called non-Newtonian, the viscosity can be altered by other means, primarily by shearing the fluid as it is stirred, poured or spread. Many household fluids are in this class, and their usefulness depends in large measure on their non-Newtonian character. The behavior of three general types of non-Newtonian fluid is my topic for this month.

In the first type of fluid the viscosity is suddenly changed by the application of a shearing force but immediately regains its normal value when the force is removed. If the shearing causes the viscosity to increase, the fluid is said to be shear-thickening. Common examples include starch solutions, quicksand, wet sand on the beach, some printer's inks and some paints. If the shearing causes the viscosity to decrease, the fluid is called shear-thinning. Mayonnaise and some paints and inks display this behavior. The advantage of shear-thinning is perhaps most apparent in ink. You want the ink in your ball-point pen to flow freely (by being sheared) as you write, but you do not want it to flow when the pen is in your pocket.



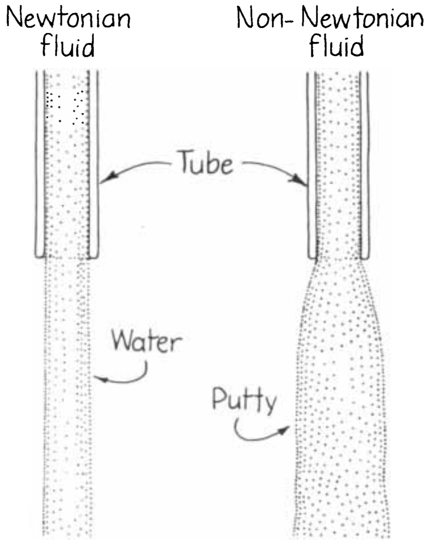
Richard E. Berg's demonstration of a dilatant fluid

The higher the rate is at which a shear-thickening fluid is sheared, the greater the viscosity will be, until finally the fluid may offer tremendous resistance to being moved. This type of behavior was first examined in detail by Osborne Reynolds beginning in 1885, when he explained fluids such as a wet sand mixture that dilates (expands) when it is sheared. Although most shear-thickening fluids appear to be dilatant, the connection is not conclusive. It does, however, provide a simple model to explain the general nature of shear-thickening fluids.

Some years ago Richard E. Berg of the University of Maryland showed me a simple demonstration of Reynolds' model for dilatant fluids. He had me squeeze a 500-milliliter plastic bottle fitted with a stopper and a clear tube at the top. He had partly filled the bottle with sand (you could also use marbles, but the effect is more difficult to see) and then had added water until the water level was in the tube at the top. When I gently squeezed the flexible sides of the bottle, the mixture inside offered considerable resistance. When I suddenly squeezed hard, the resistance was so great that I could not make the bottle collapse significantly. The water level also changed when I squeezed the bottle, but the initial change was not what one would intuitively expect: the water level went down rather than up, dropping several inches in the tube.

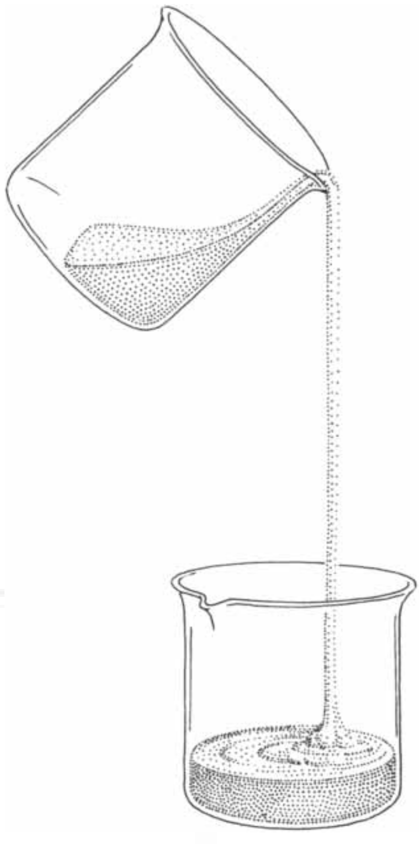
Reynolds had explained these features (for sand) by pointing out that at first the grains are packed as closely as they can be, too close to enable the surface tension of the water to pull water into all the space between grains. Berg makes certain of this close packing by tapping the bottle several times. A yielding of the mixture when it is squeezed necessarily means that some of the grains move over one another and so are typically farther away from their neighbors than they were initially. The total volume occupied by the grains therefore increases, leaving enough room between them for water to flow between the grains. Although the sides of the bottle are pushed slightly inward, this flow of water between grains decreases the water level in the container.

Reynolds' model also explained the



The phenomenon of die swell

increase in resistance to squeezing. At the moment of a sudden squeeze and the corresponding dilation the amount of water between the grains is not enough to lubricate the grains that would otherwise slide. Hence a sudden shearing produces additional friction between the grains and an increase in the apparent viscosity of the suspension. The faster the shearing is applied, the faster the grains try to move over one another and out of their closely packed state and the less sufficient the lubrication is. The mixture resists squeezing even more. Low shearing rates, on the other hand, allow water to move into the additional space between the grains to keep the friction low.



Self-siphoning in a viscoelastic fluid

A similar example can be seen at the seashore. Walk across a stretch of sand that is wet but not so wet that the grains are floating. Your footsteps will look dry and relatively white for a short time, provided you have kept your foot in place briefly. If you leave your foot in place longer, the effect is lost.

In a brief step your weight shears the sand under your foot. Since that sand was already closely packed, it can be moved only if it goes into a less closely packed arrangement. That in turn means it occupies more volume: it expands upward under your step, leaving the water level a small distance below the surface. The surface then looks dry. Eventually the water climbs up through the raised grains and on reaching the surface makes the sand look wet again.

You can easily set up this demonstration in a sandbox. To see the sand become dry under stress you could lay a thick glass plate on the sand and then carefully press down on the plate. I suggest you use a plumber's plunger to push on the glass so that you will not be cut if the glass breaks.

Quicksand is another shear-thickening fluid. A suspension of sand in water is quick when the water is under pressure from a small influx of water below the surface, such as from a natural spring. If the additional water pressure at any depth is equal to or slightly greater than the pressure of the sand at that depth, the sand grains are slightly separated and well lubricated. A heavy object placed on the top will sink to the bottom because of the low friction from the suspension.

If the suspension is rapidly sheared, the viscosity increases because the grains are initially in almost their closest packing and the shearing dilates the body of sand somewhat. As before, a sudden dilation leaves those grains less lubricated and therefore offering more resistance to the shearing. If the object is already submerged, as your leg might be in quicksand, the dilatancy would also press the quicksand more tightly about the object, making its motion even more difficult. Quicksand is not as dangerous when the influx pressure of water is high, because the grains are then well separated and the sand is not dilatant. It may even be washed away by the water current. Sand does not become quick without an influx of water, because any extra water separates out on top of a bed of closely packed sand, creating a situation similar to the ones encountered on the beach and in the demonstration with a bottle.

You can make your own quicksand. Fill a large container with sand and set up a garden hose so that it delivers water to the bottom of the container. By appropriately adjusting the water pressure from the hose you can lift the grains slightly to make the sand quick. If the water pressure is too low, a fairly heavy object placed on top of the sand will stay there. When the pressure is sufficient to make the sand quick, the object will slide through the sand to the bottom.

Most people do not know the best way to escape from quicksand. When they are caught in it, they respond by struggling. The more they struggle, however, the more they shear the quicksand and the greater are its dilatancy and apparent viscosity. If you ever step into quicksand, try to move as slowly as you can to free yourself. (Of course, you do not want to move too slowly or this entire argument will become academic.) If you have sunk up to your knees, you should lie down backward on the surface (so as to float), spread your arms and then slowly free your legs. Once they are on the surface, roll or crawl to shore, keeping your weight spread over as much of the surface as possible. If you crawl, you should push back quickly with your hands and feet, so that the shear thickening provides you with a firmer fluid.

The easiest example of a shear-thickening fluid that you can whip up in the kitchen is a simple mixture of water and cornstarch (or any common starch). Add water to the starch until the mixture is somewhat thick. When you pour this mixture or scoop it up with your hand and allow it to run back into the bowl, you will notice that it flows fairly easily and with an apparently low viscosity. Now punch your fist down into the mixture. If the viscosity remained at its previous low value, the mixture would splash all over you. The sudden shearing of the fluid, however, so greatly increases the viscosity that there is virtually no splashing, even if you hit the mixture as hard as you can. There is also little splashing if you hurl some of the fluid at the floor. This mixture is obviously great fun for the children.

If the container is fairly small, you can lift it briefly by inserting a rod into the mixture and then quickly lifting the rod. The rapid shearing increases the viscosity during the lift so that the mixture adheres to the rod.

Theories other than the one involving dilatancy have been advanced to explain shear-thickening fluids composed of suspended particles. One of the theories has the particles rubbing against one another and thereby acquiring electric charge. The increase in the viscosity is then due to the electrical attraction between individual particles.

Some shear-thickening fluids are suspensions or solutions of long-chain molecules (polymers) that are kinked and coiled. When the fluid is put under shear, the molecules are stretched and aligned perpendicular to the direction

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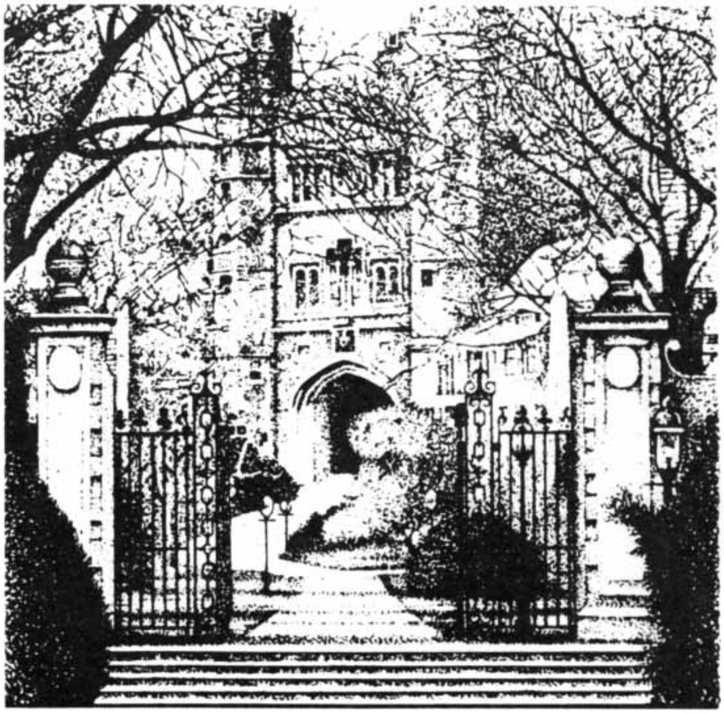

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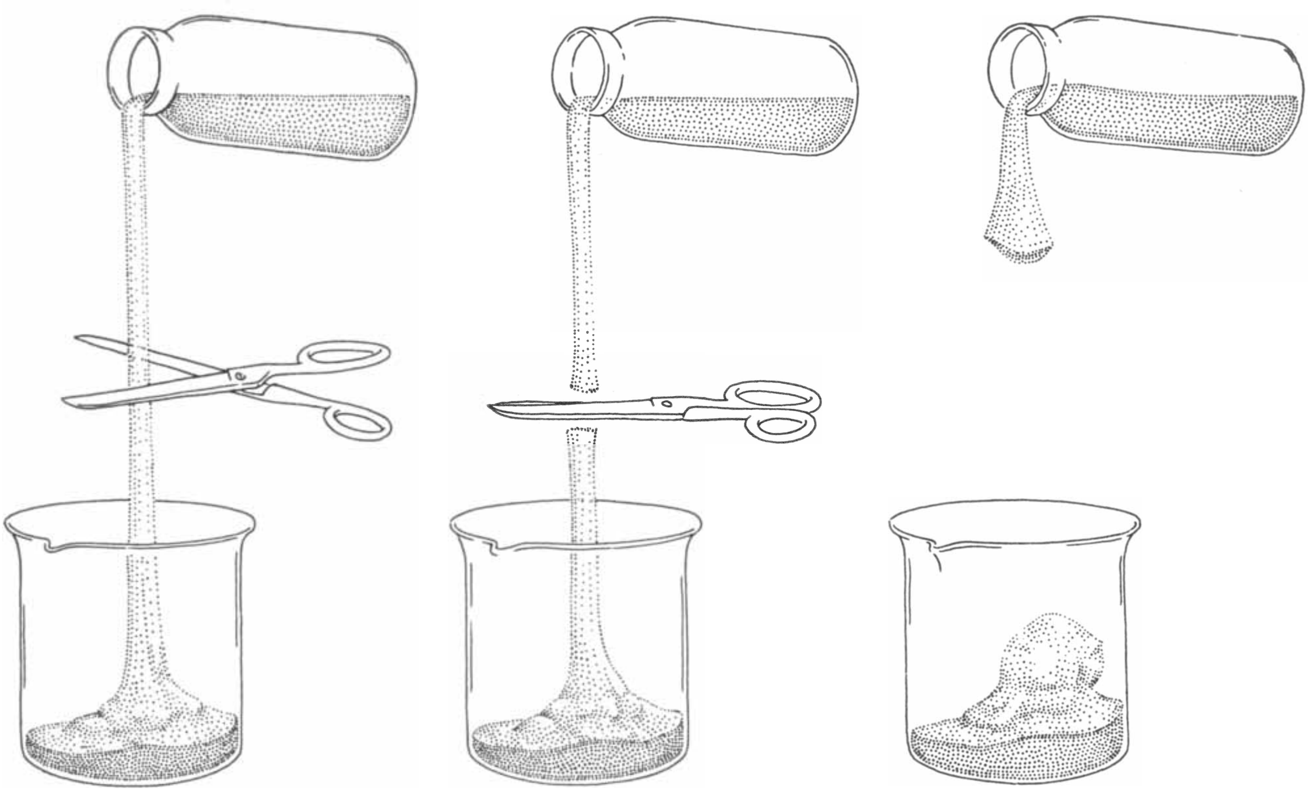


Elastic recoil in a fluid stream that has been cut

of flow, thereby increasing the apparent viscosity by inhibiting the flow. The alignment occurs almost immediately, and it disappears almost immediately when the shearing is removed.

More information on the several models of shear-thickening fluids and other non-Newtonian fluids can be found in a series of articles by A. A. Collyer of the Sheffield City Polytechnic in Britain. His publications, which are listed in the bibliography of this issue [*page 198*], are the source of many of my demonstrations.

Examples of shear-thinning fluids are not as easy to find. Collyer points out that you can make such a fluid by mixing distilled water and polyethylene oxide (often called Polyox, a registered trademark of the Union Carbide Corporation) in a .01 percent solution. ("Percent" refers to the weight of the solute with respect to the weight of the entire solution.) For the demonstrations I shall describe Polyox WSR-301 is best. It is composed of polymers with thousands of CH_2 links and with a very large molecular mass (about four million atomic-mass units). Polyox dissolves slowly in water. Collyer recommends building alternating layers of the Polyox powder and water. For three or four days keep the container covered and occasionally stir the mixture, but do not stir it vigorously or you might rupture the long-chain molecules. (The Union Carbide Corporation has generously given me a supply of Polyox WSR-301. For a small sample of the powder send a mailing label and $2 to cover postage and handling to me at the physics department, Cleveland State University, Cleveland, Ohio 44115.)

The faster a shear-thinning fluid is sheared, the lower its viscosity becomes. Eventually the shearing rate is fast enough so that the viscosity levels off at a low value. As soon as the shearing is removed the viscosity regains its former value. When the fluid is poured, portions of it appear lumpy compared with other portions, apparently because the shearing is nonuniform through the moving fluid and hence the viscosity is nonuniform too.

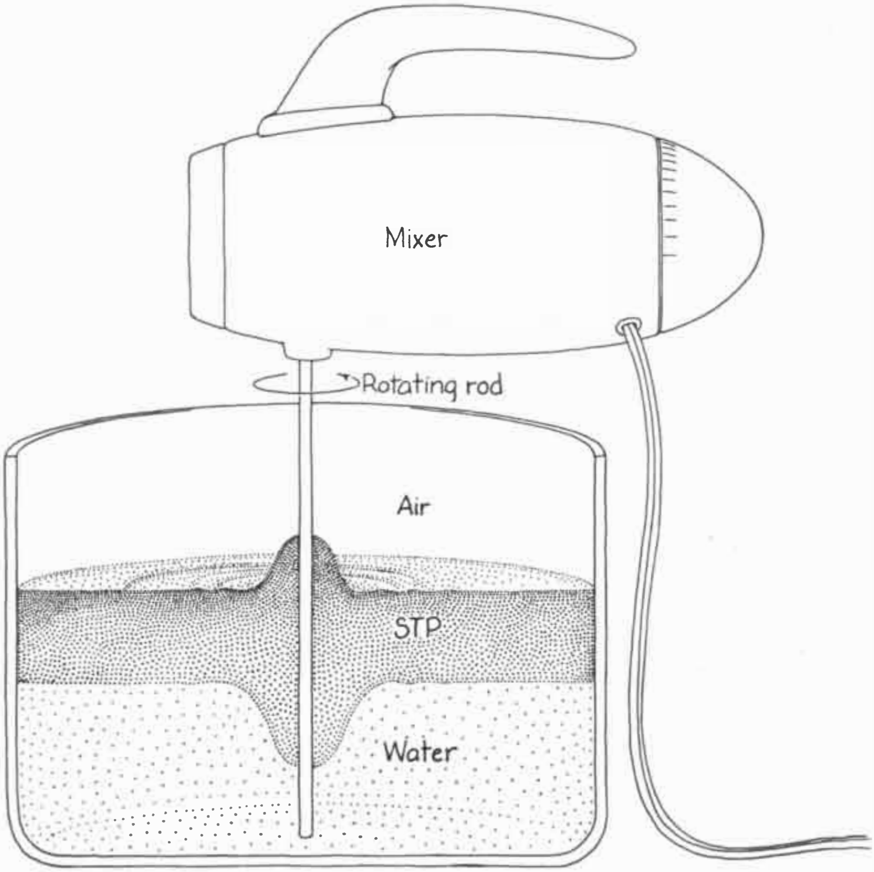
One explanation for shear-thinning is that under shearing the asymmetric particles or the long molecules in the fluid become aligned parallel to the streamlines and offer less resistance to the flow, the least viscosity resulting when all the particles or molecules are aligned. The degree of alignment depends on the shearing rate, and so therefore does the viscosity of the fluid.

Another class of non-Newtonian fluids is quite similar to the class of shear-thinning and shear-thickening ones except that the viscosity depends not only on the rate of shearing but also on how long the shearing has been applied. Once the shearing is removed a measurable amount of time is needed for the viscosity to regain its initial value. These fluids are therefore time-dependent.

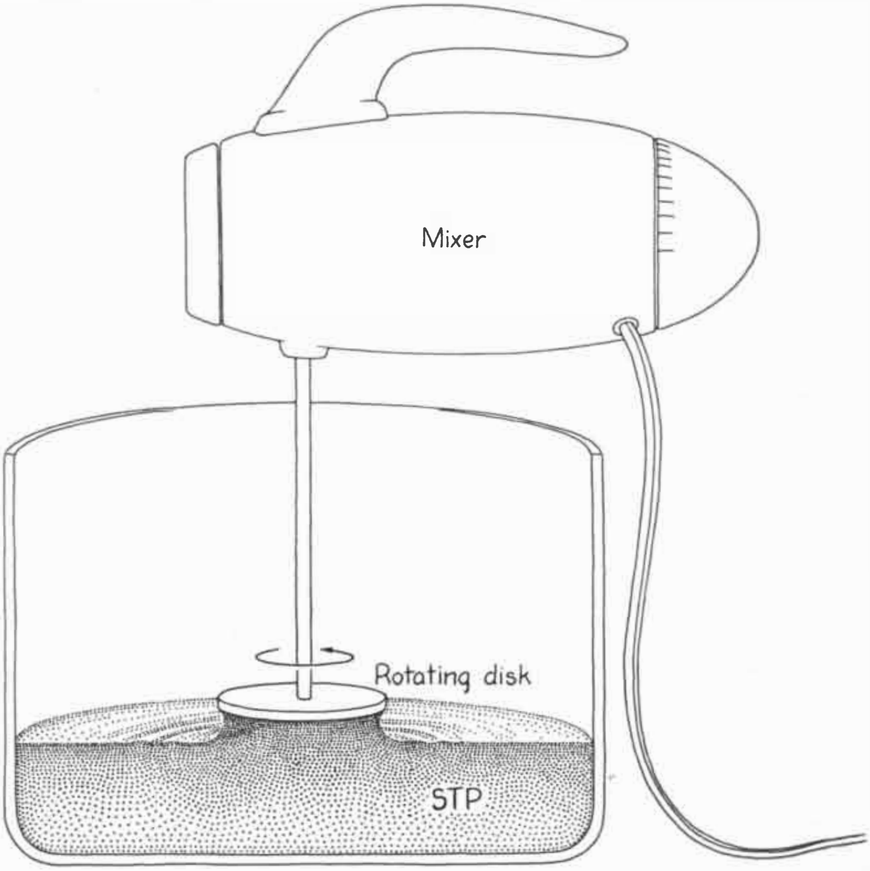
If the viscosity decreases with shearing, the fluid is said to be thixotropic; if the viscosity increases, the fluid is negatively thixotropic. Examples of the latter are few, but thixotropic fluids include margarine, some paints (such as one-coat paints), shaving cream and catsup. Margarine, for example, has a fairly high viscosity that is decreased when it is sheared across toast. If it did not behave this way, it would be more difficult to spread.

No one theory explains the change in viscosity of all thixotropic fluids. If the fluid consists of asymmetric molecules or particles, the viscosity may be decreased when they become aligned parallel to the streamlines of the sheared fluid. This model would differ from the one for shear-thinning fluids only because the bonds between molecules or particles would take longer to break or because the strength of the bonds would vary through the fluid.

For suspensions of particles of such substances as clay other theories are favored. The initial structure before shearing could be considered a gel in which the suspended particles are held in place by an ordered structure, by electrical forces between particles or by water lying between the particles. Under shearing the gel is transformed to a sol (a less solid colloidal fluid) as one of these structures is destroyed. If the thixotropic fluid is composed of polymers, one again considers alignment along the streamlines as being responsible for the change in viscosity. In addition the shearing may uncoil, disentangle and stretch the polymers to decrease the vis-



A double Weissenberg effect



The rotating-disk demonstration

cosity. Negative thixotropic fluids might be explained with a model in which the number of intermolecular bonds increases in the course of the motion. Therefore the viscosity would increase as the fluid began to gel.

Catsup can give you experience with a thixotropic fluid. If it is stirred or mixed for a few minutes, its viscosity decreases; eventually the substance becomes runny. You may have noticed this effect if you have poured catsup from a bottle just after someone has shaken it vigorously.

I tested the thixotropic nature of catsup with a simple arrangement, filling a beaker with it, allowing the fluid to stand for five minutes and then dropping small steel balls into it and timing their fall to the bottom. Since I could not see through the catsup, I put the beaker on a plastic sheet laid on a ring stand. By looking up through the plastic I could see the balls when they reached the bottom. I allowed five minutes between each fall.

After timing five falls I changed the arrangement by stirring the catsup for one minute just before each fall. The average time with no stirring was 27 seconds; with stirring it was 13 seconds. The stirring did decrease the viscosity of the catsup, and the viscosity of undisturbed fluid was not regained until several minutes after the stirring had been stopped.

The third general class of non-Newtonian fluids I shall discuss includes fluids that are elastic in addition to being fairly viscous. Examples are silicone putty, STP Oil Treatment, some condensed soups, some motor oils and the thick portion of egg white. In general the elasticity is due to the coiling of the polymers in the fluid. Shearing and stress can compress or extend these long-chain molecules, which then behave somewhat like springs.

Silicone putty, which is such a viscoelastic fluid, is derived from dimethyl silicone oil. (A laboratory procedure for its preparation was published in *Journal of Chemical Education*, Vol. 50, 1973, page 434. One type of silicone putty is sold as Silly Putty.) This substance has three interesting ranges of stress and shearing. If you shear it slowly, the putty flows like a highly viscous fluid. For example, if you suspend it from a rod, it will slowly droop downward. A somewhat faster shearing, however, causes the putty to behave like a rubber ball. Roll a ball of the putty and bounce it on the floor; its elastic recovery is fairly high. With even faster shearing the putty has almost no elasticity. If you suddenly pull on a piece, it fractures much as a metal rod does when it is stretched under tremendous strain.

By stuffing a quantity of silicone putty into a tube and pushing it through the tube you can display another interesting feature of certain elastic liquids. When the putty emerges at the other end of the tube, it expands in what is called die swell. This expansion is a nuisance in the manufacture of synthetic fibers, which also exhibit die swell when they are being spun from an orifice, because the orifice must be designed to allow for die swell in order to give the fiber the desired size and shape. Die swell can also be demonstrated with a Polyox solution of about 1 percent concentration.

The swelling appears to be a sudden recoiling against the shearing and stress of the fluid when it is being forced through the tube and the exit opening. In the tube the long-chain molecules are contracted because of the forcing. When they emerge from the tube, they suddenly expand to relieve the internal stress. If you leave the putty in the tube for a while before pushing it on through the opening, it does not expand as much. Apparently under those circumstances the stress is relieved in some other way.

Elastic recoil can also be seen in stirred solutions of Polyox and in certain condensed soups. For the Polyox, Collyer recommends a 2.5 percent solution. I tried a diluted solution of Campbell's tomato soup, following a suggestion by Peter Murphy of Centre College in Kentucky, who first pointed out the effect to me. Add one can of water to one can of condensed soup. Smoothly stir the solution with a spoon and then remove the spoon. Just as the swirling is about to die out, the direction of swirling reverses. The reversal is a recoil against the stresses and shearing that the swirling has set up in the elastic fluid.

Some elastic fluids can siphon themselves out of a beaker once you initiate a falling stream. For this demonstration Collyer recommends a Polyox solution of .8 percent. The fluid is elastic enough so that once you have a long length of it hanging from the lip of an elevated beaker, the falling length will pull more of the fluid from the beaker up to the lip and then over the side. You can reverse the direction of flow by decreasing the length of the hanging fluid. For example, allow the falling fluid to collect in another beaker and then slowly raise the second beaker to decrease the length of the fluid falling between the two.

You can see a similar climbing tendency if you suck Polyox from a beaker into a hypodermic syringe. First dip the syringe into the fluid surface and then, as you slowly pull back on the plunger, lift the syringe. The fluid continues to be drawn into the syringe even when you have raised the needle from five to 10 centimeters above the Polyox surface in the beaker. The fluid moves along that surface, reaches the thin stream to the syringe, climbs it and enters the syringe.

A stream of a 2.5 percent Polyox solution can be cut with a pair of scissors. Coat the scissors with Vaseline to eliminate sticking and then cut the stream a few centimeters below the lip of the beaker from which it is being poured. Once the cut is made, the top portion of the stream recoils upward and back into the beaker.

This effect can also be demonstrated conveniently with Slime, a new toy from the Mattel Corporation. It is a green viscoelastic fluid that displays die swell, self-siphoning, the ability to be cut and elastic recoil. It is somewhat like Silly Putty in that it has three distinct types of response to shearing and stressing. Slow shearing enables it to flow like a highly viscous fluid. After somewhat faster shearing it recoils like a rubber surface. Fast shearing causes it to fracture.

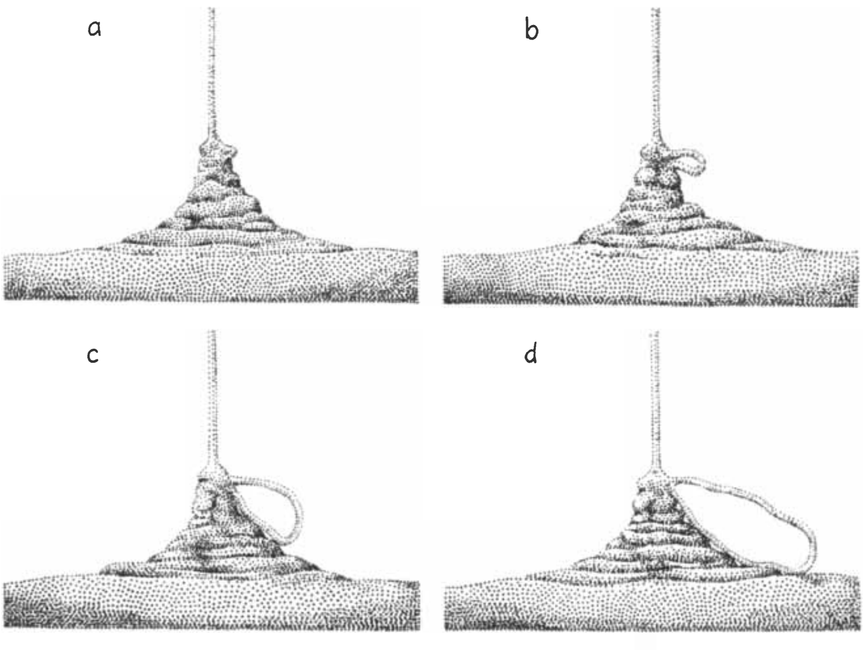
You can demonstrate two of these responses by dropping a steel ball onto the surface of Slime. The ball penetrates the surface slightly, causing the surface to oscillate as a rubber surface would. Then the ball slowly sinks into the surface and to the bottom of the Slime. Slime, which is available in most toy stores, is probably a polymer solution much like a Polyox solution. (A similar fluid called Super Liquid is available from the Edmund Scientific Company, 7875 Edscorp Building, Barrington, N.J. 08007.) The fluid is an almost irresistible toy for children and adults alike, partly because the feel and behavior of a viscoelastic fluid are so different from the feel and behavior one associates with an ordinary fluid.

To me one of the strangest effects of some of the elastic fluids is their behavior when they are stirred with a central rotating rod. Centrifugal force would cause a normal fluid stirred in that manner to form a concave surface with its lowest point in the center of the container. When an appropriate elastic fluid is stirred in this way, it does just the opposite: it moves to the center and climbs the rod in what is called the Weissenberg effect (after K. Weissenberg, who studied the phenomenon in the 1940's). Several fluids display this behavior: gelatin, some condensed milks, certain types of honey such as heather honey, STP Oil Treatment, some types of oils, Polyox and the thick portion of egg white. For Polyox, Collyer recommends a 2.5 percent solution.

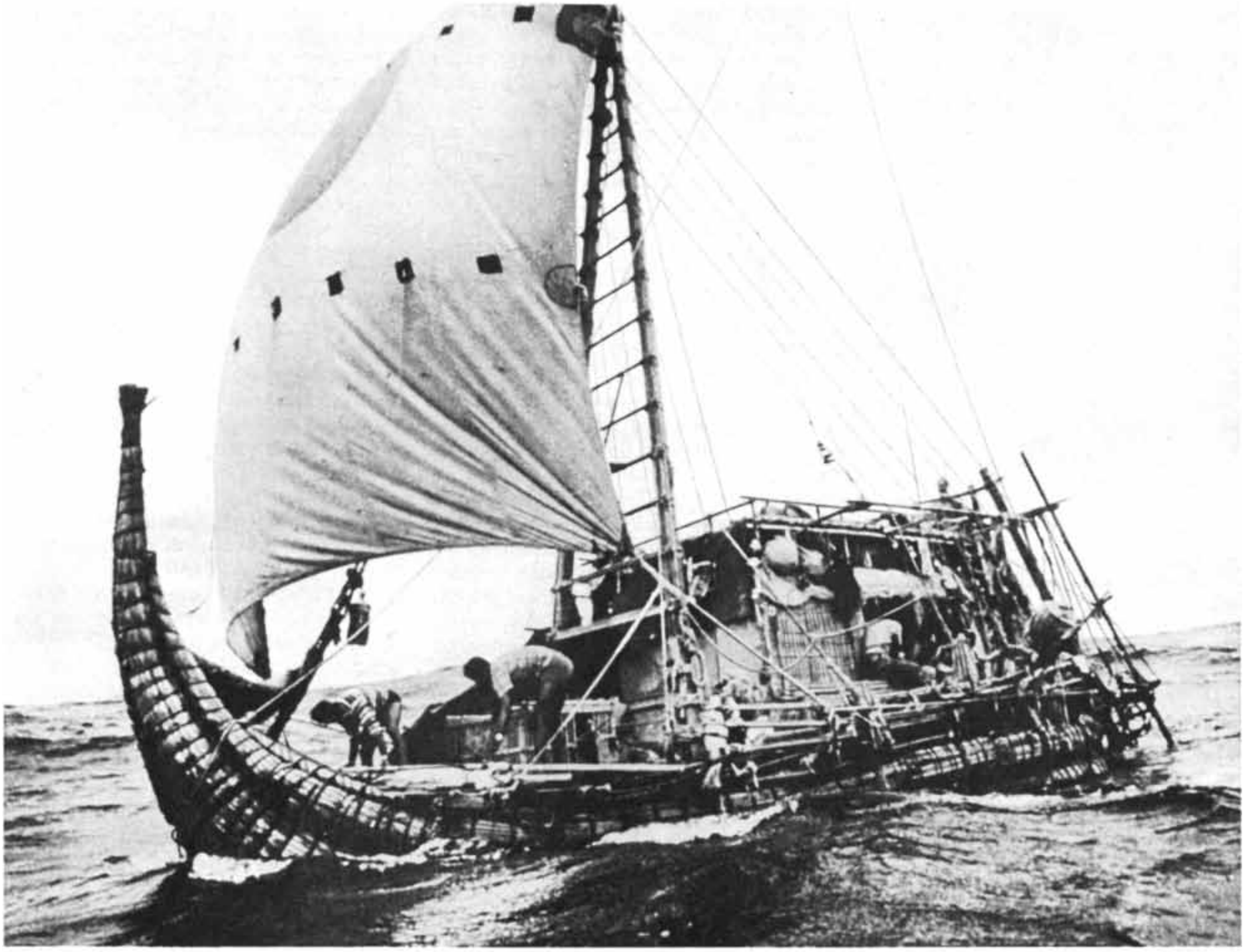
The demonstration with gelatin was described in this department in January, 1965. After the gelatin was mixed with hot water at about 130 degrees Fahrenheit, it was Newtonian until it had cooled to 86 degrees. From then until the gel point of 82 degrees was reached the mixture's climbing tendency increased as the temperature decreased.

Why does a viscoelastic fluid behave so strangely? When it is sheared in one direction, its structure causes additional forces to arise perpendicularly. In the Weissenberg effect the shearing set up by the turning rod creates a force radially inward toward the rod, pushing the fluid to and then up the rod. The greater the shearing rate is, the stronger the radially inward force is and the higher the fluid climbs. You can consider the surface as being a system of concentric elastic bands. When the bands turn at different speeds because of the fluid's viscosity, they create shearing forces between themselves, which in turn create the radial forces that attempt to make the elastic bands contract toward the center.

The same results are obtained if the rod does not rotate but the container does. Again shearing around the central rod forces fluid inward. If the rod is replaced by a hollow tube, the fluid will climb up through the tube; the faster the container is rotated, the higher



A leaping fluid showing the Kaye effect



"Sailing across the Atlantic we observed oil pollution on 43 out of 57 days"

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"When I was sailing across the Atlantic on a reed boat I had my nose literally in the water. I saw things no one can see who travels by fast boat.

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Oil pollutes the fish we eat

"On a second raft trip we sailed through water filled with lumps of oil *for 43 out of 57 days.*

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the fluid climbs. A row of tubes placed across the diameter of the fluid surface clearly shows the climbing tendency: the climbing heights increase from the tube at the rim to the tube at the center. This effect is best seen if the tubes are under partial vacuum. In certain circumstances the central object can be a flat disk held by a central rod from the top. If the disk is first lowered to the surface of the rotating fluid and then slowly lifted, it can draw the fluid up under itself.

Writing in *Journal of Fluid Mechanics,* Gordon S. Beavers and Daniel D. Joseph of the University of Minnesota recently reported obtaining the Weissenberg effect in STP Oil Treatment in a novel way. Several centimeters of the liquid were floated on a deeper layer of water, and a central rotating rod stirred both layers. The STP fluid is viscoelastic and normally displays the Weissenberg effect, but in addition to climbing up the rod into the air it also climbed down the rod into the water. Since gravity aids in pulling the STP fluid downward, the downward bulge around the rod was more pronounced than the upward bulge. If the water were replaced by a fluid with a density closer to that of STP, the downward bulge would turn out to be even larger.

If you would like to produce the Weissenberg effect, you might use a mixing bowl mounted on a turntable. You could also mount a small container on an inverted hand drill as was described in this department in the 1965 article on the Weissenberg effect in gelatin. If you prefer a central rotating rod, you could use a rod clamped into a power drill, but you should be careful not to shatter the container or splash liquid into the motor of the drill. Such a mishap could cause serious injury or even death.

I worked with a common kitchen mixer that had a variable speed control. With a hacksaw I removed the blades from a beater so that only the central rod remained. I smoothed the rod with a file. After stripping the other beater in a similar way, I glued a flat disk to the end of the beater so that I could try the disk demonstration. To control the speed better I plugged the mixer into a variable voltage control so that I could easily change the voltage to the mixer, but because this procedure might damage some mixers I would not recommend it in general.

I had little luck with Borden Eagle Brand condensed milk (which showed a small climb), Carnation evaporated milk (no climb) and partly diluted Campbell's condensed tomato soup (small climb). Egg white, however, gave a noticeable climb at the highest speed of the mixer. (Separating the egg white from the yolk is easy with an egg separator commonly sold in kitchen-supply stores.) STP worked well, climbing both up and down in the arrangement reported by Beavers and Joseph. At the highest speed of my mixer the climb into the air was about a centimeter.

In studying the Weissenberg effect you might like to try other common fluids such as different grades of motor oil and different types of elastic fluids such as honey. Different fluids could also be substituted for STP and oil in the climbing demonstration. You might correlate the depth of the downward climbing with the difference in the density of the two fluids. A third fluid (instead of air) could be added on top. In any of the Weissenberg demonstrations it would be interesting to plot the climbing height against the rotational speed and concentration of the fluid.

In 1963 A. Kaye, who is now with the Institute of Science and Technology in Manchester, noticed that when a viscoelastic solution of polyisobutylene in dekalin is poured from a height of 25 centimeters into a dish of the fluid, a thin stream occasionally leaps upward from the point of impact. This effect, now named after Kaye, operates as follows. The falling stream first creates a small heap of fluid at the point of impact. Soon a thin stream develops and flows outward from the heap in a low trajectory, eventually collapsing. Why the fluid leaps in this way was not initially understood.

Recently Collyer and P. J. Fisher pointed out that the leaping stream is actually a loop of the fluid. After examining high-speed motion pictures of the leap in order to slow down the motion they were able to propose an explanation for the Kaye effect. Because the fluid in the initial heap is moving slowly its viscosity is fairly high and the heap is therefore quite rigid. As the fluid in the stream falls its shearing rate is low and its viscosity is high. On impact, however, the shearing rate suddenly increases and the elastic fluid thins enough by shearing so that it can bounce upward from the rigid surface of the heap.

Collyer recommends mixing the polyisobutylene into the dekalin by chopping the polyisobutylene into small pieces before adding it to the liquid. Afterward the mixture must be left covered for about three weeks to complete the mixing. Collyer has written me that the Kaye effect can be demonstrated more conveniently with some types of hair shampoo, although the leaping may not be as pronounced. I tried Prell Concentrate (both in the concentrated form and in a diluted version) and Gold Circle baby shampoo. The Prell gave no effect but the Gold Circle gave occasional leaps of two or three centimeters.

The leaps last about a second, so that you must watch for them carefully or make high-speed photographs of them. To generate the leaps you should adjust the height of the shampoo container so that the stream pouring out of it is fairly narrow. Within a certain critical range of fall the stream will leap for you.

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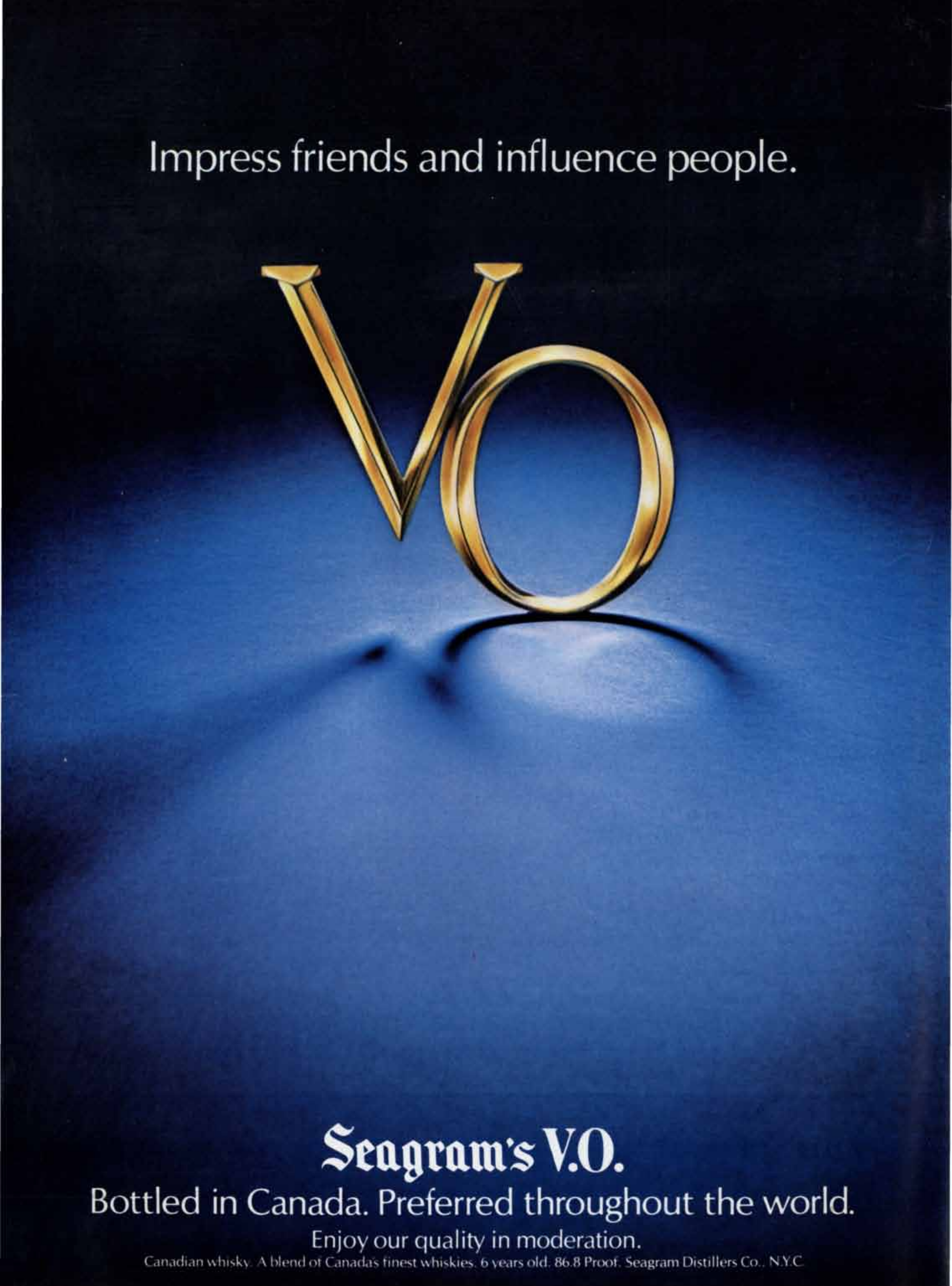

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