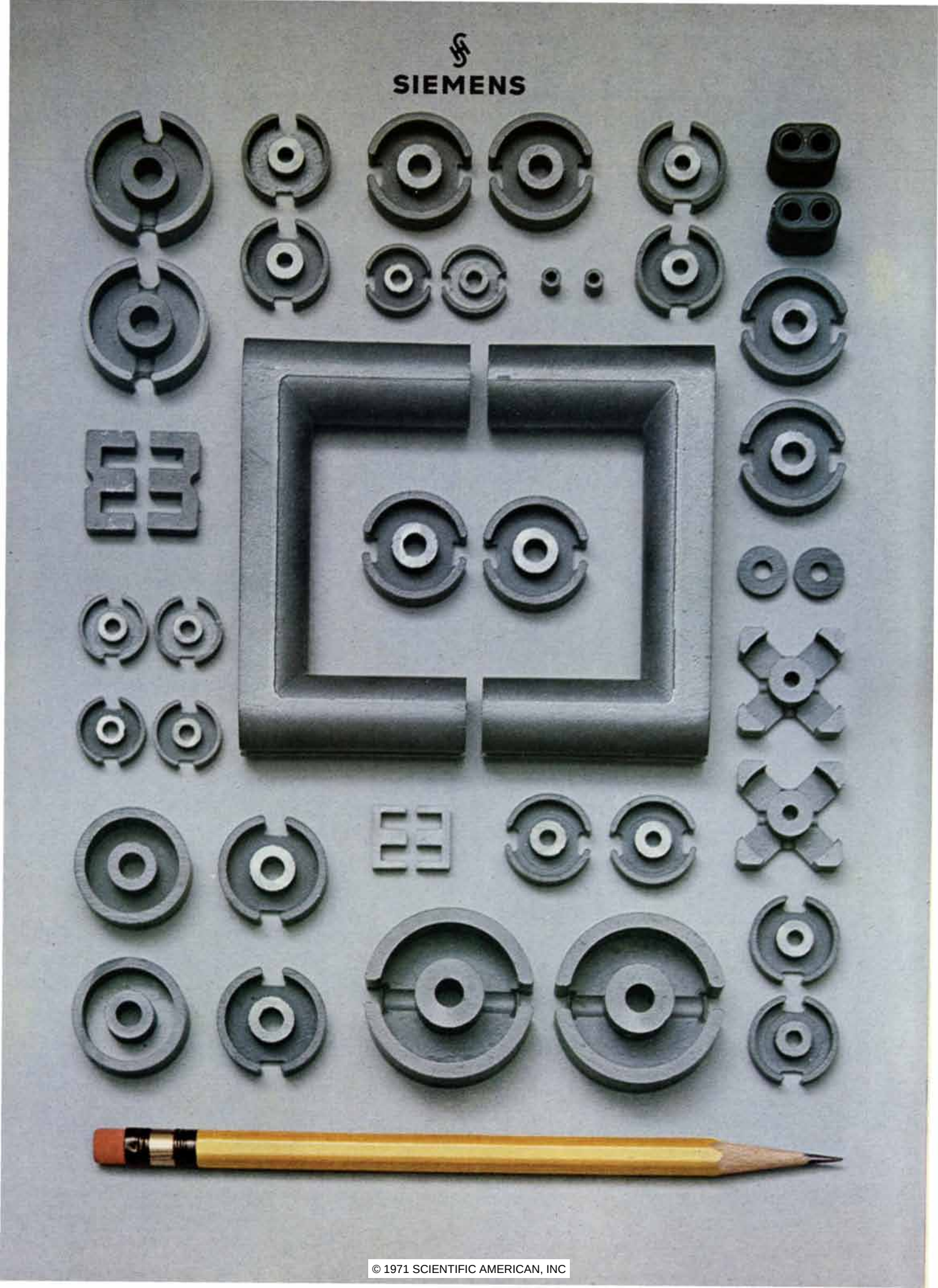
SCIENTIFIC AMERICAN

COOLING TOWER

ONE DOLLAR

May 1971



Siemens

A three billion dollar name in quality products. Deceptively simple in appearance, yet difficult to manufacture, ferrites make spectacular new products possible.

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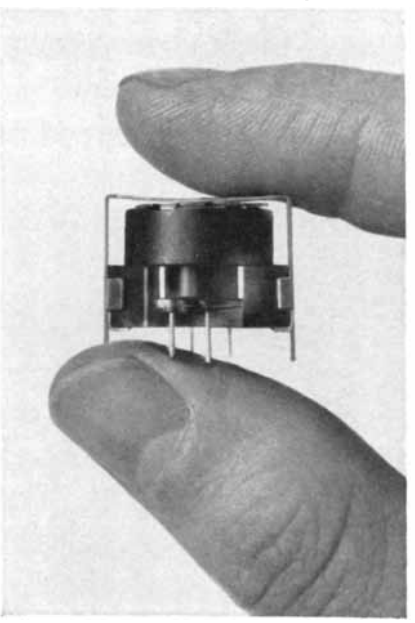

While frequency control is vital, equally significant is the low cost and small size of ferrite devices. Replacing bulky, unstable electromagnets with ferrite cores made practical one of the decade's most dramatic innovations: the videotape recorder.

The development of touch-tone telephones demonstrated another benefit of ferrite technology: flexibility. Specially designed ferrite pot cores allow stable signal transmission in a compact unit.

Computerized auto ignition systems and voltage triplers for color television also take advantage of this benefit.

As a worldwide manufacturer and user of electronic components such as capacitors, resistors, semiconductors, electron tubes and rectifiers, Siemens has designed its ferrites with total circuit requirements in mind. For more information on ferrites or other components, please write Joseph Venerus at Siemens Corporation, 186 Wood Avenue South, Iselin, New Jersey 08830.

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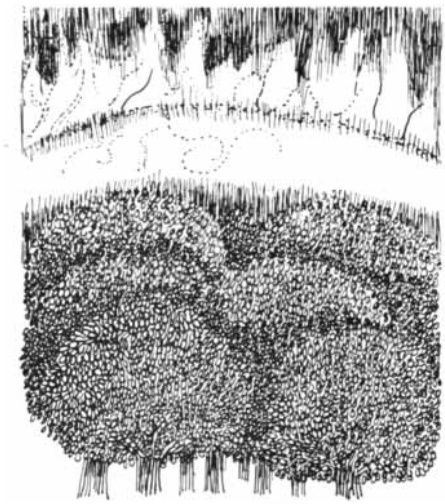

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Established 1845 **SCIENTIFIC AMERICAN** May 1971 Volume 224 Number 5

ARTICLES

DEPARTMENTS

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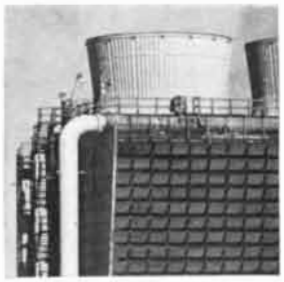

THE COVER

The photograph on the cover shows part of a cooling tower at the Northeastern Station of the Public Service Company of Oklahoma (see "Cooling Towers," page 70). It is a six-cell tower, with each cell marked by a flared stack; the photograph therefore shows one cell and part of another. Adjacent to this tower is another six-cell tower. Together they receive about 345 million gallons of water a day from the condensers of the power station's 470,000-kilowatt unit, which generates electricity by burning natural gas. The water is delivered to the tower by the large pipes at left. From the top of the tower, just below the railing, the water falls downward, being broken up into fine droplets by horizontal slats called "fill." Air drawn in through the louvered sides of the tower by a large fan inside the stack is pulled across the path of the falling water. The air cools the water, mainly by evaporation, and then is discharged from the stack. The cooled water collects in a basin at the bottom of the tower and is recirculated to the power plant. Two smaller towers serve a 170,000-kilowatt unit at the station.

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Cover photograph by Ben Rose

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LETTERS

Sirs:

The conclusions of Michael C. Corballis and Ivan L. Beale ["On Telling Left from Right"; SCIENTIFIC AMERICAN, March] seem astounding in the face of profound evidence. They conclude: "In general, therefore, it appears that left-right asymmetries are particularly associated with the kinds of behavior that are no longer restricted to the natural environment. This conclusion reemphasizes our point that the large majority of left-right asymmetries exist only in the man-made environment."

It would seem that perhaps these authors have overlooked one of the most fundamental distinctions between living and nonliving matter: the pronounced asymmetry of biological molecules. To cite but one example, consider the amino acids found in living organisms. Chemical synthesis of an amino acid would yield equal amounts of the dextrorotary ("right-handed") and levorotary ("left-handed") forms of that amino acid, but biosynthesis will consistently yield only one single form (with rare exceptions). To extend this example to asymmetry of perception, consider the fact that L-leucine has a bitter taste, D-leucine has a sweet taste and the racemic mixture (both) is tasteless. Indeed, most biochemical reactions are distinguished by their discriminatory symmetry. Such a conclusion as the authors have reached seems untenable in the face of overwhelming evidence to the contrary.

FRANCIS W. SAYRE

School of Pharmacy
University of the Pacific
Stockton, Calif.

Sirs:

In our article we note that "most higher animals, including man, are in fact almost bilaterally symmetrical in terms of gross body structure and the anatomy of the nervous system." Although we do not make it explicit, we assume throughout that we are dealing with symmetries and asymmetries at these levels and not at the molecular (or for that matter the subatomic) level.

Nevertheless, Professor Sayre raises an interesting point, because the observations he makes are consistent with our general thesis that only asymmetrical systems can tell left from right. Where analysis is presumably at a neural level, as in vision or touch, mirror-image discrimination causes trouble. Where the analysis is chemical, as in taste or smell, mirror-image discrimination is easy. In an earlier and more detailed article ("Bilateral Symmetry and Behavior," by M. C. Corballis and I. L. Beale; *Psychological Review,* Vol. 77, No. 5, page 451, 1970) we put it: "Mirror-image discrimination is readily achieved at the molecular level, as we might expect from the structural asymmetry of organisms at this level. Chemical stereoisomers, whose molecules are mirror-images of one another, often taste and smell different from one another. For example, geraniol smells like roses while its stereoisomer smells like fresh oil."

MICHAEL C. CORBALLIS

McGill University
Montreal

IVAN L. BEALE

Dalhousie University
Halifax, N.S.

Sirs:

I read with great interest the article by J. Julian Chisolm, Jr., on lead poisoning [SCIENTIFIC AMERICAN, February]. Dr. Chisolm observes that the danger of lead intoxication "has been rediscovered periodically since antiquity." In Goethe's famous novel *Die Wahlverwandtschaften* there is an illustration of this fact, indicating that knowledge of lead poisoning was quite widespread late in the 18th century. Goethe wrote (Part I, Chapter 4): "Because she liked to stay alive she attempted to suppress everything that was harmful and deadly. The lead glaze of earthenware and the verdigris of copper vessels caused her much worry. She had herself been taught about it, and naturally one had to go back to the basics of chemistry and physics."

H. HIRSCHEL, M.D.

Thun, Switzerland

Sirs:

In the March issue of *Scientific American* ["Letters"] Richard S. Watt indicates that the significance of Martin Luther King's initials, M. L. K., is clear to one with a little knowledge of biblical Hebrew. He further stipulates that the Hebrew word for king is *melek,* and that since Hebrew is a consonantal language *MLK* can be interpreted to signify king. In actuality the Hebrew word for king is *melech,* the *ch* being a guttural sound bearing no relation to the letter *k,* which has a different symbol in the Hebrew alphabet.

Mr. Watt goes further and asserts, correctly, that Hebrew is written from right to left, giving a sequence to the initials of Dr. King's name of *KLM.* To give this cabalistic game one more gambit, *KLM may* be interpreted as *cholam,* the Hebrew word for dream.

JOEL R. COHEN

Springfield College
Springfield, Mass.

Sirs:

Having just read Theodore H. Savory's article on the mule and its near relatives [SCIENTIFIC AMERICAN, December, 1970], I think some of your readers may enjoy reading one of the minor classics from the literature of the mule written by Justice Oliver of the Nebraska Court of Appeals, wherein he makes a fine distinction between an ex-

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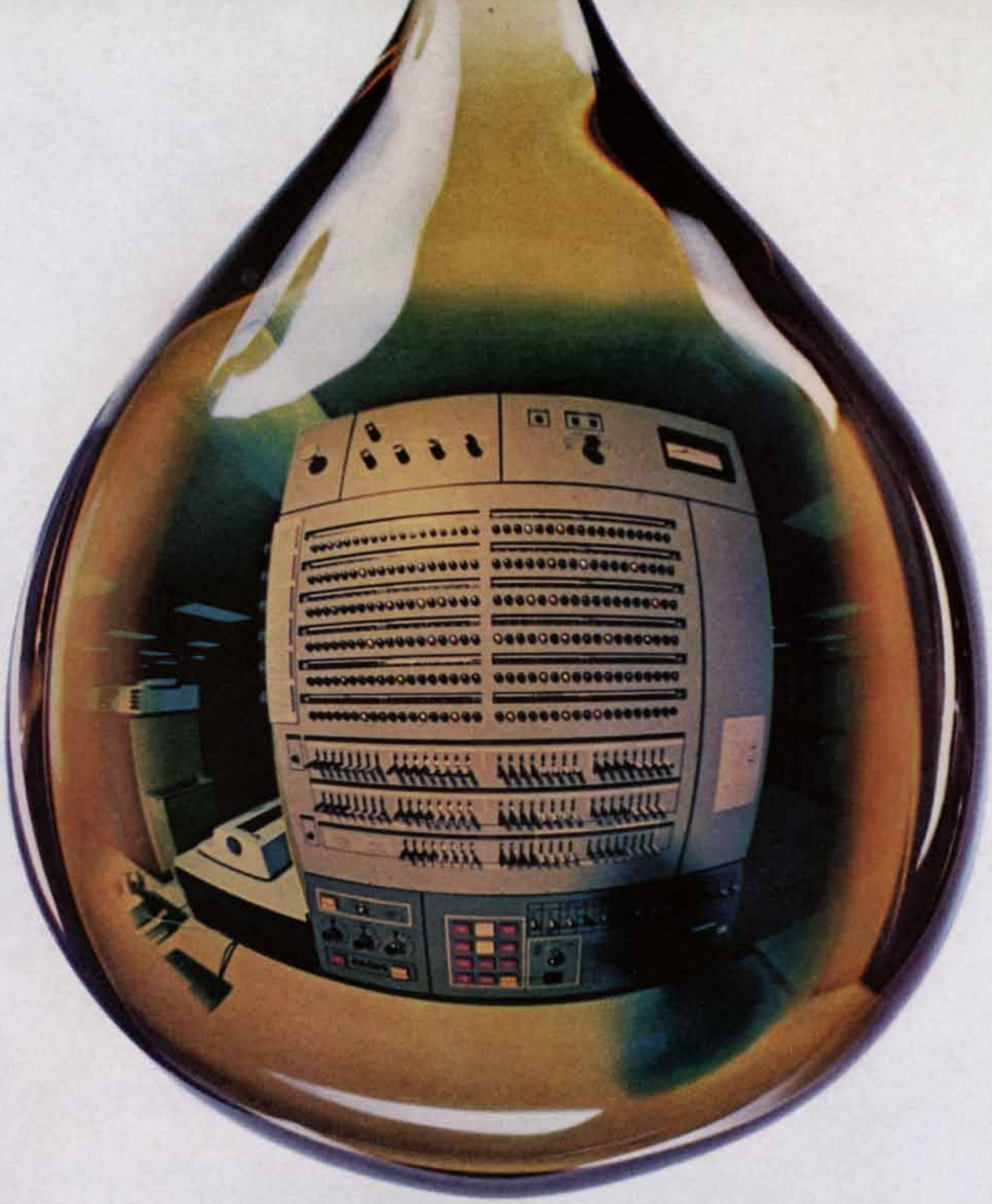
OLD ADDRESS



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You get a body and a frame that has been "unitized" or welded together instead of just bolted. (Bolts can rattle loose.)

With the Sportabout, you don't have to worry. It's easy to handle, and it's stylish.

And it comes at a price that may make you laugh.

American Motors

press warranty and an implied warranty. Commonly called the Celebrated Jackass Case, it is to be found in 121 Neb. App. 72, and it is quoted here in its entirety:

"The evidence before the Court is amply sufficient to establish an express warranty on the part of the defendant that the animal in question was a fit and suitable one for breeding purposes, and the Court therefore finds that there was a warranty. But even conceding that there was no warranty, there surely can be no question, under the evidence, that there was an implied warranty as to its fitness as a breeder and foal-getter. The defendant must surely have known that the plaintiff was purchasing the animal for breeding purposes only. He knew at the time of making the sale that no reasonable man would attempt to use a jackass for any other purpose than to outrage nature by propagating mules. He could not have supposed that the plaintiff desired to acquire a jackass for a pet. The animal is wholly unsuitable for that purpose. Its form is neither pleasing to the eye, nor its voice soothing to the ear. He is neither ornamental in his appearance, nor amusing in his habits; he is valuable only as he is able and willing to propagate the mule species.

"It appears from the evidence that after purchasing the animal, the plaintiff on several occasions caused him to be placed in the society of certain soft-eyed, sleek-coated young mares, that were in the pink of that condition which is supposed to arouse the interest and attract the attention of any reasonably amorous jackass, but that he passed them up and knew them not. The defendant admits representing to the plaintiff that the jackass in question would do that work for himself. But evidence shows that if he was ever possessed of that valuable and charming accomplishment, he failed on the occasions just mentioned to practice it with the zeal and ardor becoming of an ambitious jackass in full possession of his faculties.

"He was, indeed, a worthless, unpedigreed and impotent jackass, without pride of ancestry or hope of posterity—a source of disappointment to his female friends, and an item of expense to his owner. There is no brute in all the animal kingdom more worthless than a Missouri-bred jackass afflicted with lost manhood. He was not as represented and warranted by the defendant, and the plaintiff is entitled to recover."

HARVEY C. MCCALEB

Columbia, Mo.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1921: "The problem of the world's supply of energy is the subject of an interesting discussion published recently by Dr. Arrhenius. It is pointed out that the early exhaustion of our fossil fuels will require the use of such other sources of power as water, wind and sun. The estimated life of the coal fields is put down at 1,500 years, and he believes it to be clear that we must soon ration our coal and substitute as far as possible other sources of energy. In view of the greatly increased use of petroleum, it is considered doubtful that mineral oils will constitute an adequate auxiliary supply. Dr. Arrhenius calculates that the continual increase of carbon dioxide in the atmosphere from the burning of coal will give the whole world a more uniform and warmer climate."

"The luster of the Curie family continues undiminished. Mme Curie (who will receive her gram of radium at the hand of President Harding in Washington on May 20) has just succeeded in determining the respective proportions of radium and mesothorium, a factor that has hitherto baffled the savants who have considered mesothorium as being more powerful. Meanwhile Prof. Laporte, a cousin of Mme Curie, has discovered a new method for measuring the speed of gaseous emanations, and Mlle Curie, a niece of Mme Curie, has succeeded in determining the atomic weight of some substance the name of which is garbled in cable transmission."

"According to Lord Haldane, mustard gas was not known in Europe before the war, yet 48 hours after it was first used by the Germans, British chemists had run it to earth. It was not discovered by the Germans during the war, as has so often been erroneously stated. When Lord Haldane was a student at Göttingen, he often walked around the walls of the university town and noted the chemical laboratory just outside. Professor Meier was in charge, and he came across the gas many years ago. He recorded the discovery officially, and two British men of science remembered the paper he had written and identified the gas."

"Professor Reuterdahl's recent article in the *Dearborn Independent* is given its real place by the scare-head of the cover, which asks, in 3/4-inch letters, 'Is Einstein a Plagiarist?' It will be at once understood that according to Professor Reuterdahl he is. We expect this sort of thing from the anti-Semites of Germany and from those of the Kaiser's loyal supporters who resent Dr. Einstein's refusal to have anything to do with the celebrated Manifesto of the 93 Immortals. But from a reputable American source—even one celebrated for its anti-Semitism—we should look for something a little different. Never in the history of science has anyone ever made an epoch-making advance but what the vultures have flocked about his trail, demanding credit for what he has done and claiming ownership of the work which he has put out. But never before has it been the case that the really big men of science have accepted an advance so promptly and so whole-heartedly, and left this business of picking the bones to the small fry whose names will be forgotten 50 years from now."

SCIENTIFIC AMERICAN

MAY, 1871: "Can any one grasp the exceedingly probable fact that in 1900—only 29 years from now—the population of the U.S. will number 75,000,000? Yet, says the *Evening Mail,* Mr. Samuel F. Ruggles proves that this will be the case. When, therefore, the ablest, most experienced and most trust worthy statistician now living tells us that we shall have a population of 75,000,000 in 1900, the younger part of the present generation may as well consider what awaits them in their maturity and old age. Seventy-five millions of people in the U.S. implies the settlement of the entire South and West by as dense a population as that of Massachusetts; the reclamation of the arid wastes of the Great Plains by irrigation; the development of states as strong as Ohio, Indiana and Illinois along the Rocky mountains; the settlement of the Utah basin by four or five millions of agricultural and pastoral people; the development of a tier of agricultural states along our northern border from Lake Superior to the Pacific as populous and prosperous as Missouri and Minnesota; the growth of the Pacific states into commonwealths as rich and populous as New York and Pennsylvania. It means that New York will cover the whole of Manhattan Island with a population of at least two millions, to say nothing of the outlying suburbs in New Jersey and across the East River."

"Dr. Clerk Maxwell, F.R.S., recently exhibited some remarkable experiments on light and color. In the course of the lecture he called attention to the fact that all persons have a yellow spot upon the retina, which tends to make color vision somewhat imperfect. To make the presence of this spot sensible to the observers, Dr. Maxwell projected a disk of light upon a screen and colored the disk by making the light pass through a solution of chloride of chromium. The light thus produced is of a red color, mixed very largely with greenish-yellow rays which are copiously absorbed by the yellow spot. He then told the observers to wink slowly at the disk, and they nearly all then saw large red cloud-like spots floating over the disk, in consequence of the absorption of most of the rays, with the exception of the red, by the yellow spot in the eye. When the disk was gazed at steadily without winking, the floating red clouds disappeared."

"Abbé Moigno's journal, *Les Mondes,* for September 8, 1870, has just arrived. It was too heavy to be sent by balloon during the siege of Paris and had to come during the lucid interval that existed after the evacuation by the Germans and before the unfortunate civil war. It is to be hoped that the abbé has not shared the fate of many of the clergy and that his valuable scientific journal has not been suppressed."

"Some idea of the popularity of base ball, that excellent out-door amusement, may be gathered from the following report on the manufacture of base balls and bats, which we find in the New York *Times:* No fewer than 16 kinds of balls are in use, from the regulation ball to the children's or fancy ball, and prices vary from $18 to 85 cents a dozen. The town of Natick, Mass., is the greatest ball manufactory in the world, many hundreds of people being employed in producing these articles, and it is not uncommon for houses in this line of business to order thence 6,000 balls at a time. The total number of balls made and sold in New York is immense, one manufacturer alone having supplied 162,000 balls last year. Bats form an important business by themselves. It sounds somewhat preposterous to think of mills running all the year round, turning out bats."

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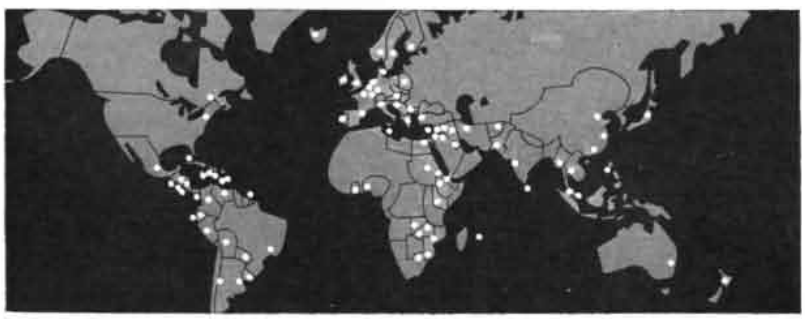

IT'S 50 YEARS LATER

50 JAHRE ANS YEARS AÑOS 1921 1971 WILD HEERBRUGG

THE AUTHORS

LEONARD J. GOLDWATER ("Mercury in the Environment") is professor of community health sciences at Duke University and professor of environmental sciences in the School of Public Health of the University of North Carolina. "Never received a high school diploma but now hold four university degrees," he writes. They include an M.D. obtained from the New York University School of Medicine in 1928. Goldwater taught at N.Y.U. from 1933 to 1941 and at the Columbia University School of Public Health from 1946 to 1969. During many of those years he also operated a 100-acre farm in New Jersey. "Migrated from New York to North Carolina partly to be in golf country," he says, "but have been too busy to indulge the habit to any extent. I like bridge and music, particularly oratorio. Raise a vegetable garden and one of the best lawns in the area. Love to be associated with young people. Hate sham, dishonesty and hypocrisy."

JOSEPH WEBER ("The Detection of Gravitational Waves") is professor of physics at the University of Maryland. He was graduated from the U.S. Naval Academy in 1940 and served in the Navy until 1948. Taking up graduate work in physics at the Catholic University of America, he obtained his Ph.D. in 1951. He was professor of electrical engineering at the University of Maryland from 1948 to 1959, when he received his present appointment. His interests outside his work, he writes, include "photography, mountaineering, classical music and hi-fi."

ELSO S. BARGHOORN ("The Oldest Fossils") is professor of botany at Harvard University, curator of paleobotanical collections at the Harvard Botanical Museum and a member of the department of geology at the university. During the past three years he has in addition been a principal investigator in the Apollo space program. "My early interests in science," he writes, "were in astronomy, then chemistry, botany and finally paleontology. In college [Miami University of Ohio] I had a conflict between my yen for the track team and for the laboratory. At one point I quit college to work as a deckhand. I have long had photography as a hobby and still have, but I suppose I can also call myself an amateur farmer and gardener, since I enjoy raising my own vegetables and hay crop and maintaining an Angus per year for beef." Barghoorn has been associated with Harvard most of the time since 1937, when he entered as a graduate student. He received his master's degree there in 1938 and his Ph.D. in 1941.

MAARTEN SCHMIDT and FRANCIS BELLO ("The Evolution of Quasars") are respectively professor of astronomy at the California Institute of Technology and associate editor of SCIENTIFIC AMERICAN. Schmidt is also a member of the staff of the Hale Observatories (formerly the Mount Wilson and Palomar Observatories) and a staff member of the Owens Valley Radio Observatory. Born in the Netherlands, he took his Ph.D. at the University of Leiden in 1956. In the same year he came to the U.S. as a Carnegie fellow, going to Cal Tech in 1959. "My interests were initially comets, the spiral structure of our galaxy and the distribution of mass in our galaxy," he writes. "Later they evolved to star formation, radio galaxies and quasars. Other interests are music, hiking and loafing, but too little time is found for each of these."

RILEY D. WOODSON ("Cooling Towers") is executive partner with the Kansas City firm of Black & Veatch, consulting engineers. He is head of the firm's power division and in that capacity is involved not only with cooling systems for large plants but also, he notes, "design of more than 10 million kilowatts of electric generation and several high-voltage transmission projects." Woodson has been with the firm since 1935, when he was graduated from the University of Kansas with a degree in mechanical engineering.

GEORGE SHIERS ("The Induction Coil") is a free-lance technical writer and consultant and the author of several textbooks on electronics. He teaches courses in scientific and technical writing and in adult-education training for the University of California extension at Santa Barbara. His activities include work with the Institute of Electrical and Electronics Engineers and the Society of Technical Writers and Publishers. He and his wife are completing *Bibliography of the History of Electronics.* Shiers was the author of "The First Electron Tube" in the March 1969 issue of SCIENTIFIC AMERICAN.

WHITMAN RICHARDS ("The Fortification Illusions of Migraines") is associate professor of psychology at the Massachusetts Institute of Technology. "My undergraduate education at M.I.T. went very fast (two and a half years)," he writes, "thanks to an excellent preparation at Phillips Exeter Academy. My major emphasis was on math, physics and metallurgy. This background provided a technical overkill for subsequent sales engineering of temperature-measuring devices, which was my profession for six years. Bored by the routine of business life, I began exploring other fields, particularly in the life sciences, to find a more stimulating career. In 1961 I returned to M.I.T. and three years later became the first doctoral candidate in psychology. The challenges offered by problems of sensory physiology and perception seem to me to be awaiting solution; the field of discovery is very fertile, much as physics was 100 to 200 years ago. The joy in tackling each little problem is like reading an endless suspense novel; each chapter begins with a bit of mystery and ends with a partial solution that creates further mystery."

JOHN H. TODD ("The Chemical Languages of Fishes") is an assistant scientist at the Woods Hole Oceanographic Institution. He writes that because his interests as a child in Canada included farming, he "went to McGill University to study agriculture in order to acquire the skills to farm" but found that "agriculture was not taught as a biological pursuit but as just another chemically sanitized and mechanized business, which turned me away from agriculture." He took his bachelor's degree in biology in 1961 and his master's degree at McGill's Institute of Parasitology in 1963. In 1963 and 1964 he worked for a biological consulting firm in Canada and conducted environmental studies throughout the country. After obtaining his doctorate at the University of Michigan, he taught ethology at San Diego State College until going to Woods Hole in 1970. Todd writes of his optimism "that we will be able to predict from behavioral studies the fate of populations in polluted environments." He adds that his major interest apart from his work "is new-world planning," as exemplified by the New Alchemy Institute, of which he is president. He describes its purpose as seeking "alternatives that would aid the biosphere and man," in part by creating "a new biotechnology based on an ecological ethic, which in turn will provide the foundation for small humanitarian decentralist communities throughout the country."

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Mercury in the Environment

The metal is widely distributed, mostly in forms and amounts that do no harm. The question is whether its concentration by industrial and biological processes now endangers animals and human beings

by Leonard J. Goldwater

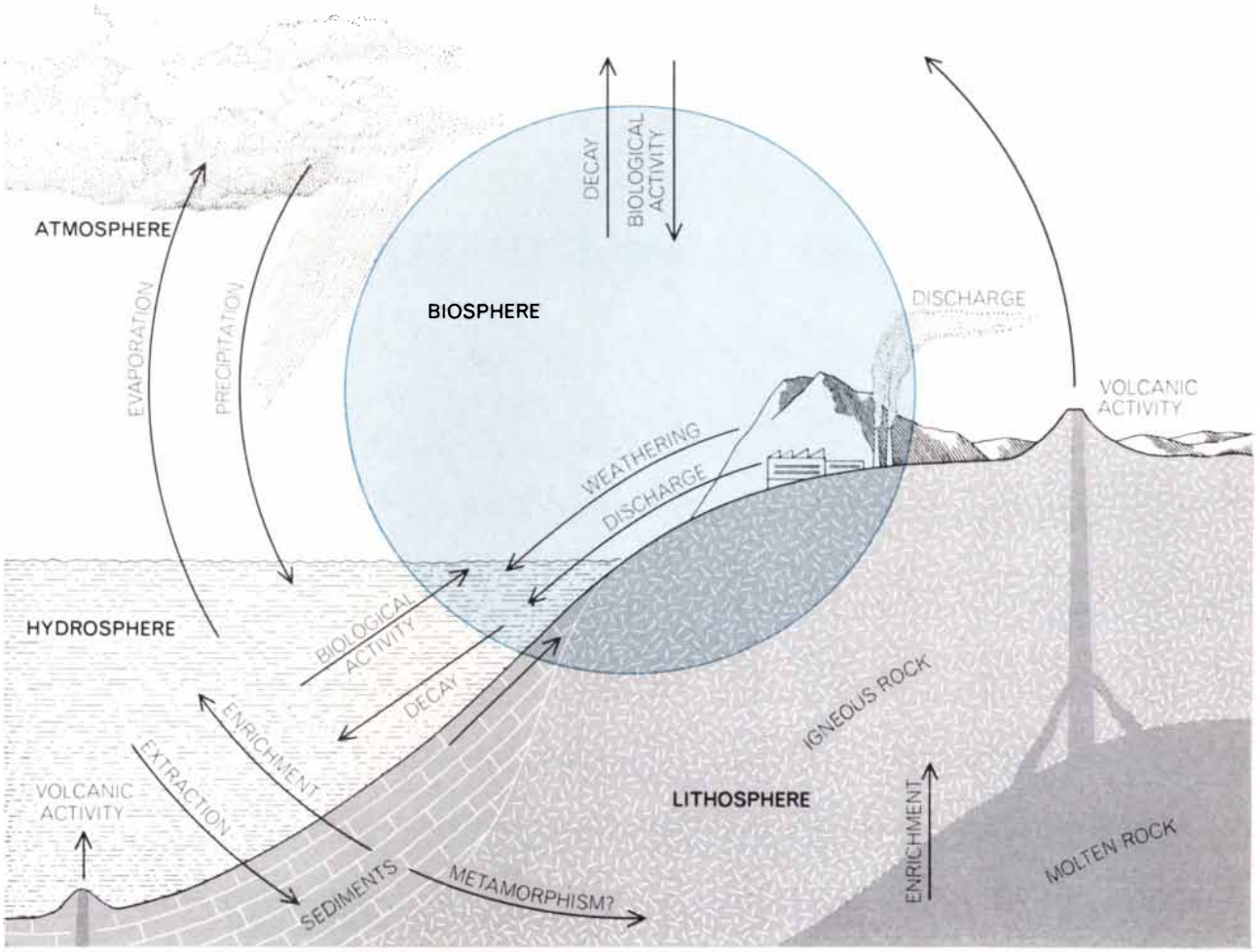
In the early 1950's fishermen and their families around Minamata Bay in Japan were stricken with a mysterious neurological illness. The Minamata disease, as it came to be called, produced progressive weakening of the muscles, loss of vision, impairment of other cerebral functions, eventual paralysis and in some cases coma and death. The victims had suffered structural injury to the brain. It was soon observed that Minamata seabirds and household cats, which like the fisherfolk subsist mainly on fish, showed signs of the same disease. This led to the discovery of high concentrations of mercury compounds in fish and shellfish taken from the bay, and the source of the mercury was traced to the effluent from a factory.

Since then there have been several other alarming incidents. In 1956 and 1960 outbreaks of mercurial poisoning involving hundreds of persons took place in Iraq, where farmers who had received grain seed treated with mercurial fungicides ate the seed instead of planting it. There were similar outbreaks later in Pakistan and in Guatemala. In Sweden, where poisoning of game birds and other wildlife, apparently by mercury-treated seeds, began to be noticed in 1960, the Swedish Medical Board in 1967 banned the sale of fish from about 40 lakes and rivers after it was found that fish caught in those waters contained high concentrations of methyl mercury. In 1970 alarm rose to a dramatic pitch in North America. Following the discovery of mercury concentrations in fish in Lake Saint Clair by a Norwegian investigator working in Canada, restrictions on fishing and on the sale of fish were imposed in many areas in the U.S. and Canada, and government agencies in both countries began to take action to control the discharge of mercury-containing wastes into lakes and streams.

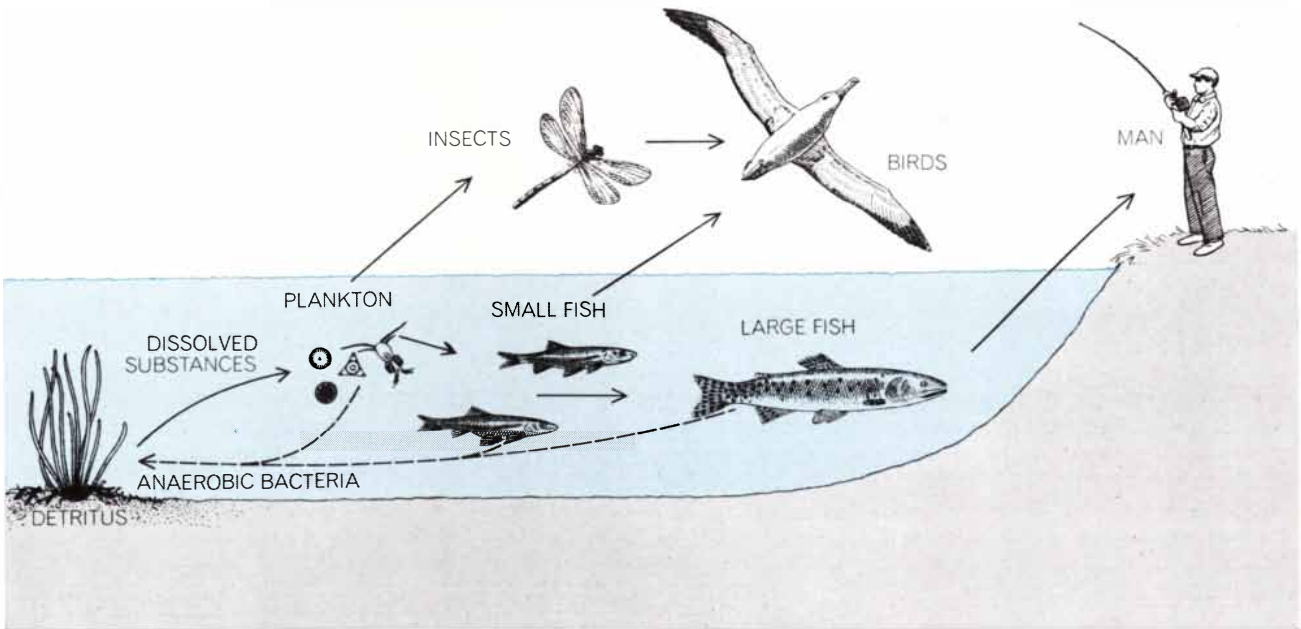
Suddenly, almost overnight, mankind has become acutely fearful of mercury in the environment. The alarm is understandable. Quicksilver has always been regarded as being magical and somewhat sinister, in part because of its unique property as the only metal that is a liquid at ordinary temperatures. Mercury's peculiarities have been recognized since medieval times, when the alchemists took a keen interest in the element's fascinating properties. Its toxic properties became so well known that some mercury compounds came to be used as agents of suicide and murder. There are indications that Napoleon, Ivan the Terrible and Charles II of England may have died of mercurial poisoning, either accidental or deliberate. (Charles II experimented with mercury in his laboratory.) It has been suggested (incorrectly) that mercury is what made Lewis Carroll's Hatter mad (since it is used in the manufacture of felt hats). And it is authentically recorded that as early as 1700 a citizen of the town of Finale in Italy sought an injunction against a factory making mercuric chloride because its fumes were killing people in the town.

Nevertheless, although the recent incidents give us justifiable concern about the potential hazards of mercury in the environment, a panicky reaction would be quite inappropriate. Mercury, after all, is a rare element, ranking 16th from the bottom of the list of elements in abundance in the earth and comprising less than 30 billionths of the earth's crust. There are comparatively few places in the world where it occurs naturally in more than trace amounts, and the ore-bearing deposits of commercial value are so limited that a handful of mines scattered over the globe account for most of the world production. The uncompounded element in liquid form is not a poison; a person could swallow up to a pound or more of quicksilver with no significant adverse effects. Nor should it be forgotten that certain compounds of mercury have been used safely for thousands of years, and some are still prescribed, as effective medications for various infections and disorders. We need not shrink from mercury as an unmitigated threat. What is now required is detailed investigation of how mercury is being redistributed and concentrated in the environment by man's activities and in what forms and compounds it may be harmful to life. Extensive research on these questions is under way.

We consider first what might be called the normal distribution of mercury in nature. The element is found in trace amounts throughout the lithosphere (rocks and soil), the hydrosphere, the atmosphere and the biosphere (in tissues of plants and animals). In the rocks and



MERCURY CYCLE disperses the metal through the lithosphere, hydrosphere and atmosphere and through the biosphere, which interpenetrates all three. Mercury is present in all spheres in trace amounts, but it tends to be concentrated by biological processes. Man's activities, in particular certain industrial processes, may now present a threat by significantly redistributing the metal.



AQUATIC FOOD CHAIN is a primary mechanism by which mercury is concentrated. At each trophic level less mercury is excreted than ingested, so that there is proportionately more mercury in algae than in the water they live in, more still in fish that feed on the algae and so on. Bacteria and the decay chain (*broken arrows*) promote conversion of any mercury present into methyl mercury.

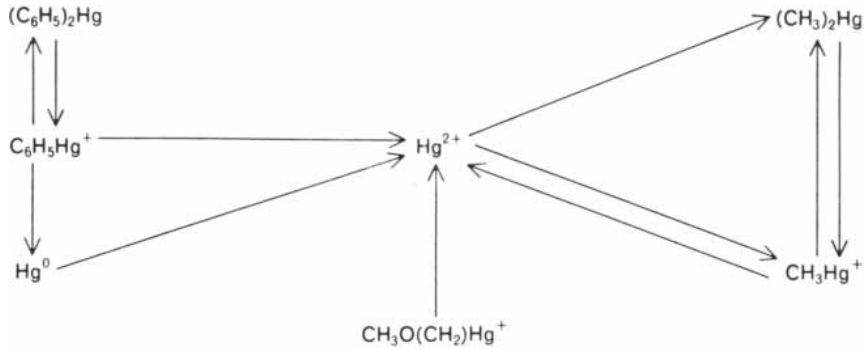
soils (apart from ore concentrations) mercury is measured in fractions of one part per million, except in topsoils rich in humus, where the amount may run as high as two parts per million. In the hydrosphere (the seas and fresh waters) it generally occurs only in parts per billion. In the atmosphere mercury is present both as vapor and in the form of particles. Under natural conditions, however, the amount is so small that extremely sensitive methods are required to detect and measure it; the measurements that have been made at a few locations indicate that this atmospheric "background" amounts to less than one part per billion. The situation is somewhat different when we come to the biosphere. Plants and animals tend to concentrate mercury; it has been found, for example, that some marine algae contain a concentration more than 100 times higher than that in the seawater in which they live, and one study of fish in the sea showed mercury concentrations of up to 122 parts per billion. There is considerable variation, as we shall see, in the amounts of mercury found in plants and animals, depending on circumstances. Under natural conditions, however, the concentration in the earth's vegetation (aside from cultivated plants) averages no more than a fraction of one part per million.

Thus the natural cycle of circulation of mercury on the earth [*see top illustration on opposite page*] disperses it widely through the habitable spheres in trace amounts that pose no hazard to life. How seriously has man altered its distribution?

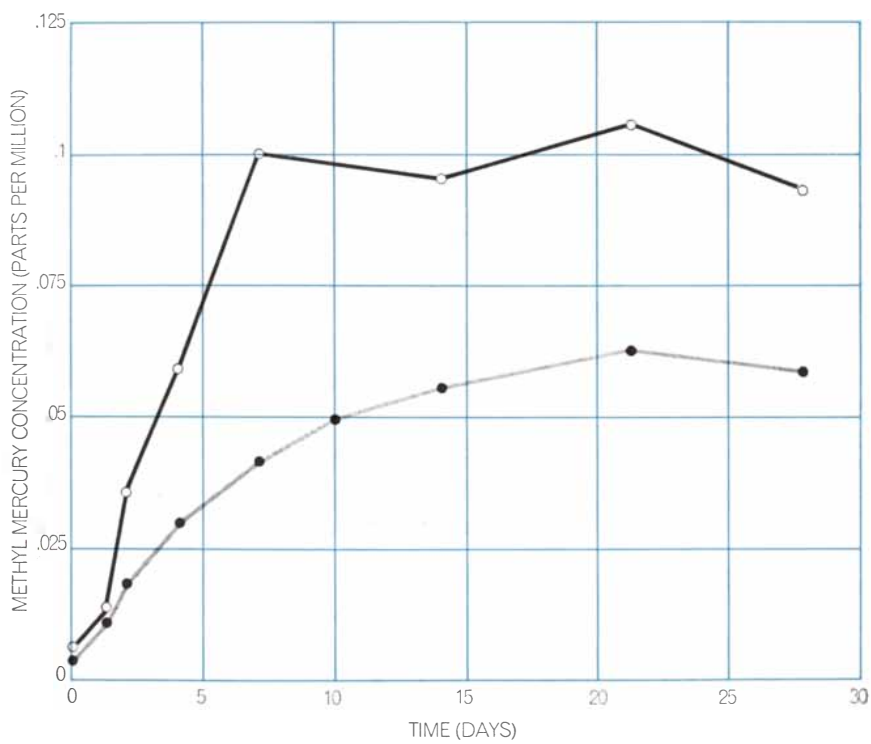
The only ore containing mercury in sufficient concentration for commercial extraction is cinnabar, or mercuric sulfide (HgS). There are minable cinnabar deposits in many regions around the world, and man was attracted to its use as early as prehistoric times. There is evidence that cinnabar was mined in China, Asia Minor, the Cyclades and Peru at least two or three millenniums ago. Cinnabar, a brilliant red mineral, came into use at first as a pigment, but it was not until medieval times that physicians and other investigators became interested in extracting quicksilver from ore to produce medicines and other useful compounds. Hippocrates is believed to have prescribed mercury sulfide as a medication, and this was probably one of the first compounds of a metal to be employed therapeutically.

By the Middle Ages, when alchemists had synthesized chlorides, oxides and various other inorganic compounds and mixtures of mercury, its use in medications began to spread. Calomel (mercurous chloride, or HgCl) came into wide use as a cathartic, and in the 16th century mercury compounds were introduced as a treatment for syphilis. By the 19th century scores of mercurials were being employed in medicine. Many are still in the pharmacopoeias; the most useful ones today are the diuretics. It has been found that even among the organic compounds of mercury there are some that can be used safely. As much as 78.5 grams of mercury in the form of an organic compound has been given to a patient without harmful side effects!

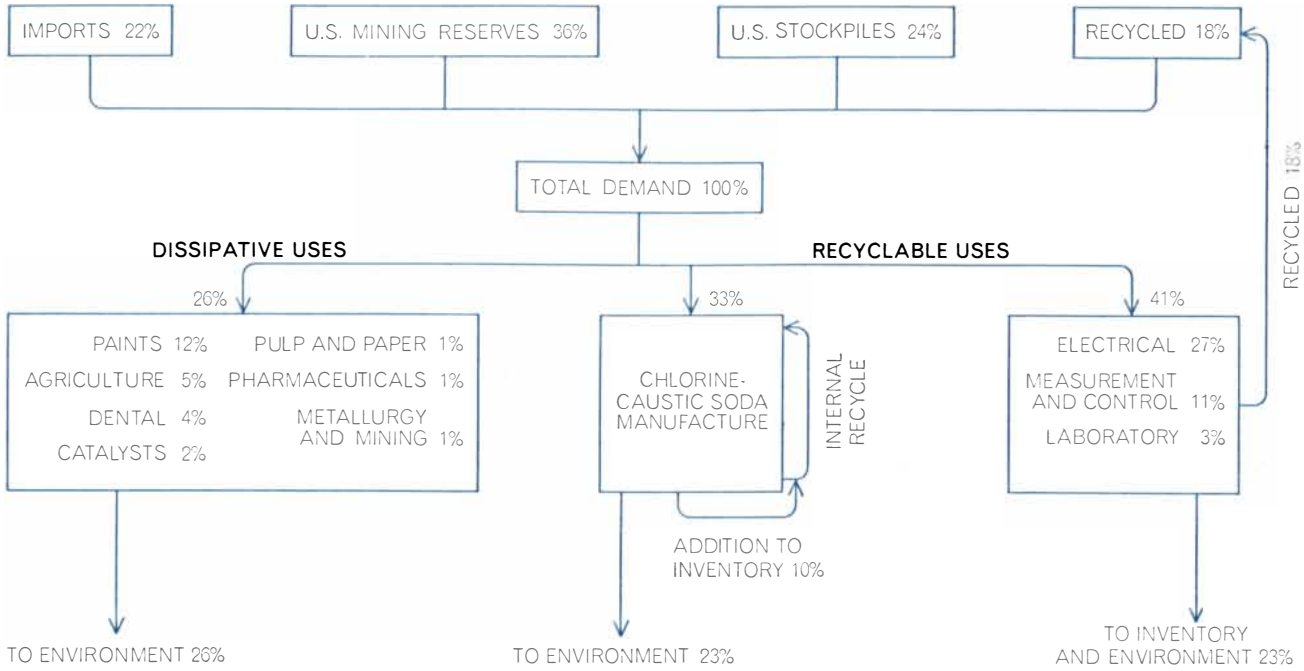
The use of cinnabar as a coloring agent and of mercury compounds in pharmaceuticals under careful control introduced no threat to the quality of the environment. With the development of other applications, however, particularly in industry and agriculture, came serious problems. The extraction of mercury from the ore by heating (that is, distillation) dangerously contaminates the air in localized areas with mercury vapor and dust (as the protesting citizen of Finale observed nearly three centuries ago). Mercury today is used on a substantial scale in chemical industries, in the manufacture of paints and paper and in pesticides and fungicides for agriculture. The world production of mercury



METHYL MERCURY COMPOUNDS are the most injurious ones. According to Arne Jernelöv of the Swedish Water and Air Pollution Research Laboratory, mercury discharged into water in various forms can be converted by bacteria in detritus and sediments into methyl and dimethyl mercury (*right*). Phenyl mercurials, metallic mercury and methoxyethyl mercury (*left and bottom*) are converted into methyls primarily through ionic mercury.



CONVERSION of inorganic into methyl mercury in sediment was measured by Sören Jensen and Jernelöv at intervals after the addition of 10 (*gray*) and 100 (*black*) parts per million of inorganic mercury. At lower mercury concentrations methylation may not occur.



MERCURY FLOW through the U.S. is shown for 1968. The chart is based on one prepared by Robin A. Wallace, William Fulkerson, Wilbur D. Shults and William S. Lyon of the Oak Ridge National Laboratory. Major use of mercury has been as a cathode in the electrolytic preparation of chlorine and caustic soda. In this process a large inventory of mercury is continuously recycled, but in 1968 23 percent of total mercury demand still went to make up what was wasted. Another 10 percent went for start-up of new plants. Since then legislation and lawsuits have required manufacturers to increase recycling sharply, reducing emissions to the environment.

now amounts to about 10,000 tons per year, of which about 3,000 tons are used in the U.S. (The principal producers are Spain, whose mines at Almadén are the richest in the world, Italy, the U.S.S.R., China, Mexico and the U.S.) From the large-scale uses a considerable amount of mercury wastes is flowing into the air, the soil and streams, lakes and bays.

In agriculture, for example, corrosive sublimate ($HgCl_2$) is used to disinfect seeds and to control many diseases of tubers, corms and bulbs (including potatoes). The chlorides of mercury (both mercuric and mercurous) are also employed to protect a number of vegetable crops. In recent decades farmers in Europe and the U.S. have adopted the use of organic compounds of mercury, some of which are highly toxic, principally to prevent fungal diseases in seeds and in growing plants, fruits and vegetables. These chemicals may present a potential threat to health through the ingestion of treated seeds by birds (and people), through concentration in food plants and through percolation or runoff from the fields into surface waters. The U.S. Geological Survey, after analyzing the concentration of mercury in a number of U.S. rivers in 1970, reported that although the mercury content was only one part per 10 billion or less in most rivers and streams, "it may be several thousand times this concentration in some natural waters."

In order to evaluate the hazards of mercury in the environment we must examine the forms in which it occurs there and the relative toxicity of its various compounds. Liquid mercury itself, as we have already noted, is not ordinarily toxic to man. Inhalation of mercury vapor, however, can be injurious. In acute cases it causes irritation and destruction of the lung tissues, with symptoms including chills, fever, coughing and a tight feeling in the chest, and there have been reports of fatalities from such exposure. The acute exposures, however, usually come about not from the general environment but by accident, such as heating a household mercurial. More common is a chronic form of injury resulting from occupational exposure to mercury vapor, for example among mercury miners and workers in felt hat factories employing mercury nitrate for processing. These exposures, as we have found in examinations of miners, are not necessarily incapacitating; they produce tremors, inflammation of the gums and general irritability.

The soluble inorganic salts of mercury have long been known to be toxic. Mercury bichloride (corrosive sublimate), which has been used on occasion for suicide and homicide, produces corrosion of the intestinal tract (leading to bloody diarrhea), injury to the kidneys, suppression of urine and ultimately death from kidney failure when it is taken by mouth in a substantial dose. Its former use in moderate doses by mouth for treatment of syphilis did not, however, result in observable poisoning in most cases. Mercurous chloride is less soluble than the mercuric salt and therefore is less dangerous. It is still used medicinally, but some of its uses have been abandoned because it was found to cause painful itching of the hands and feet and other symptoms in children. Among other inorganic mercurials, some of the oxides, such as the red oxide used in antifouling paint for ship bottoms, may be potentially hazardous. In general, however, these inorganic mercurials are not important factors in contamination of the general environment.

What does cause us concern now with regard to the environment is the presence of some of the organic compounds of mercury, specifically the alkyls: the methyl and ethyl compounds. In Minamata Bay the substances that had poisoned the fish and people were identified as methyl mercurials. The grain that caused outbreaks of illness and death among the farmers of Iraq had been treated with ethyl mercury *p*-toluene sulfonanilide. And alkyls of mercury were similarly incriminated in Sweden and other places.

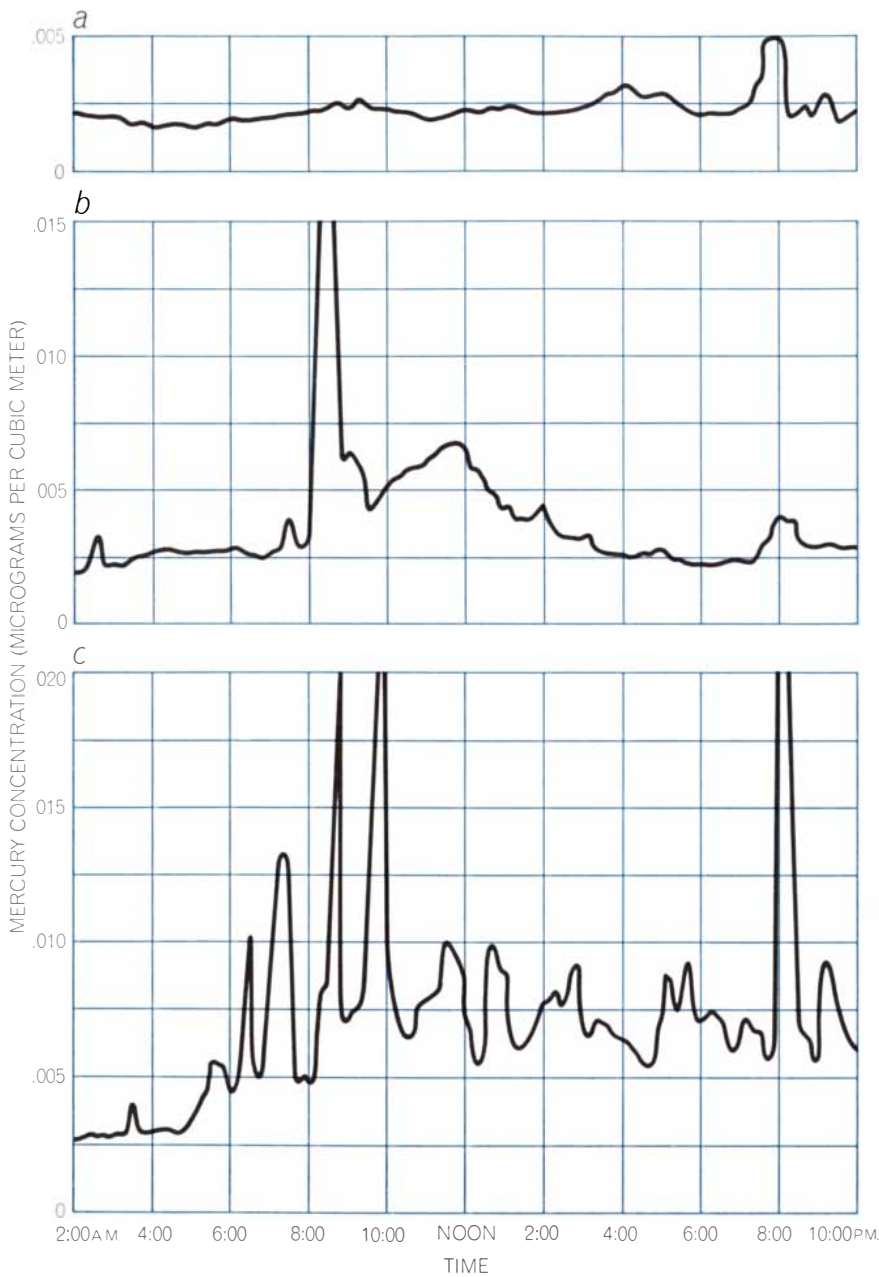
It has been known for some time that alkyl mercury can cause congenital mental retardation, and recent laboratory studies have shown that it can produce abnormalities of the chromosomes and, through "intoxication" of the fetus in the uterus, can bring about cerebral palsy. The alkyl mercurials attack the brain cells, which are particularly susceptible to injury by this form of mercury. The chemical basis of this effect seems to be mercury's strong affinity for sulfur, particularly for the sulfhydryl groups (S-H) in proteins (for which arsenic and lead have a similar affinity). Bound to proteins in a cell membrane, the mercury may alter the distribution of ions, change electric potentials and thus interfere with the movement of fluid across the membrane. There are also indications that the binding of mercury to protein disturbs the normal operation of structures such as mitochondria and lysosomes within the cell. Alkyl mercury appears to be especially dangerous because the mercury is firmly bonded to a carbon atom, so that the molecule is not broken down and may maintain its destructive action for weeks or months. In this respect it differs from the inorganic and phenyl (aryl) mercurials, and that may explain why it produces permanent injury to brain tissue, whereas the injury caused by inorganic and aryl mercurials is almost invariably reversible.

At one time it was thought that aryl mercurials (compounds based on the phenyl group) might act like the alkyls; however, in an extensive series of studies I initiated in 1961 at the Columbia University School of Public Health we found that chemical workers who continually handled phenyl mercurials and experienced exposures far above the supposedly safe limit did not show any evidence of toxic effects.

Having examined the nature of the mercury "threat" and its quantitative presence in the environment, we should now look at the other side of the equation: the extent of man's exposure and his response to this factor up to now.

Without question the major source of man's intake of mercury is his food. Alfred E. Stock in Germany initiated analyses of the mercury concentration in foods in the 1930's, and there have been several follow-up studies since then, including one by our group at Columbia in 1964. (Numerous further investigations are now in progress.) The measured concentrations in samples from various sources are in the range of fractions of one part per million [*see illustration on next page*], but the concentrations in fish in contaminated waters may run several hundred times higher than that. A joint commission of the Food and Agriculture Organization and the World Health Organization proposed in 1963 that the permissible upper limit for mercury in foods (except fish and shellfish) should be .05 part per million; there is as yet no firm basis, however, for determining what the safe standard ought to be. Perhaps the most significant conclusion that can be drawn from these sets of samplings is that in general the concentration of mercury in foods does not appear to have changed substantially over the past 30 years. The comparisons may not be entirely valid, however, because of differences in analytical methods.

In addition to food, there are other possible everyday sources of exposure to mercury. It is used fairly commonly in antiseptics, paint preservatives, floor waxes, furniture polishes, fabric softeners, air-conditioner filters and laundry preparations for suppression of mildew; no doubt there are other such exposures



ATMOSPHERIC MERCURY LEVELS were measured by S. H. Williston at a station south of San Francisco. The concentration averaged about .0002 microgram of mercury per cubic meter of air when the wind blew from the Pacific (*a*) and was somewhat higher when the wind was from the generally nonindustrial southeast (*b*). The average was .008 microgram, with many peaks that went off the record at .02 microgram, when the wind was from the industrial area to the northeast (*c*). The mercury was often associated with dust particles.

of which we are not aware. In view of all these factors, it is not surprising to find that 20 to 25 percent of the "normal" population—persons who have apparently had no medicinal or occupational exposure to mercury—show easily measurable amounts of mercury in their body fluids. Several studies of this matter have been made, including a fairly extensive international investigation we carried out at Columbia in 1961–1963 as a joint project with the WHO. Analyzing 1,107 specimens of urine collected from "normal" subjects in 15 countries, we found that except in rare instances the mercury content in the urine ran no higher than about 20 to 25 parts per billion. A similar examination of blood samples showed that the highest mercury concentration in the blood among "normal" subjects was 30 to 50 parts per billion. And analyses of human tissues made at autopsy have indicated that similar traces of mercury are present in the body organs.

It is important to consider these findings in the context of the evolutionary relationship of life on our planet to the presence of mercury. Unquestionably the element has been omnipresent in the sea, where life originated, from the beginning, and presumably all plants and animals carry traces of mercury as a heritage from their primordial ancestry. Man as the top of a food chain must have added to that heritage by eating fish and other mercury-concentrating forms of food. Over the millions of years he presumably has built up an increased tolerance for mercury. (The development of tolerance for chemicals is of course well recognized today. It was put to use more than 2,000 years ago by Mithradates the Great, king of Pontus, who armed himself against poisoners by taking small and increasing doses of toxic agents.) Tolerance for a potent substance not infrequently grows into dependence on it, and it is reasonable to suppose that man, as well as other forms of life, may now be dependent on mercury as a useful trace element. Whether its effects are beneficial or harmful may be influenced decisively by the form in which it is incorporated in tissues, by the dose and probably by other factors. It has been found, for instance, that the highly toxic element arsenic is sometimes present in healthy shrimp in concentrations of close to 200 parts per million (dry weight) in the form of trimethylarsine. Methylation in this case apparently suppresses the element's toxicity. The biochemical behavior of mercury has much in common with that of arsenic, which suggests that there may be harmless forms of methyl mercury as well as toxic ones in fish.

Our concern, then, must be with any disturbance of the environment that alters the natural balance of mercury in relation to other substances or that generates virulent forms of mercurials. In the case of the fish in Minamata Bay apparently both factors were at work. The polluting effluent from the chemical plant itself contained methyl mercury, and elemental mercury in the effluent was methylated by microorganisms in the mud on the bottom of the bay. This conversion was fostered by the enrichment of the water with a high concentration of mercury and organic pollutants that promoted the growth of the methylating bacteria. The result was the accumulation in the fish of concentrations of methyl mercury as high as 50 parts per million (wet weight), which is 100 times the *total* mercury concentration currently accepted as "safe" in the U.S. and Canada. The effect on the fishermen and their families was compounded by the fact that their diet consisted largely of the bay fish and may have been deficient in some essential nutrients; dietary deficiencies are known to enhance the adverse effects of toxic agents.

The current journalistic outcry on the "mercury problem" has produced a state of public alarm approaching hysteria. "Protective" measures are being proposed and applied without basis in established knowledge. Research on mercury poisoning in the past has focused primarily on occupational hazards involving prolonged exposure, principally by way of inhalation. Mercury in the general environment, however, presents an almost entirely different problem. Discharge of mercury into the atmosphere, either as vapor or as particulate matter, is not likely to become a serious general hazard. The main threats to which we shall have to give attention are solid and liquid wastes that may ultimately enter bodies of water, thus threatening fish and eaters of fish, and agricultural uses of mercury that may dangerously contaminate food. We do not yet have enough information to estimate the magnitude of these threats or to establish realistic standards of control.

To begin with, we need a better understanding of what should be considered a toxic level of mercury in the human body. Analysis of the mercury con-

	A	B	C	D	E
MEATS	.001–.067	.005–.02	.0008–.044	.31–.36	.001–.15
FISH	.02–.18	.025–.18	.0016–.014	.035–.54	0–.06
VEGETABLES (FRESH)	002–.044	.005–.035	0	.03–.06	0–.02
VEGETABLES (CANNED)			005–.025		.002–.007
MILK (FRESH)	.0006–.004	.0006–.004	003–.007	.003–.007	.008
BUTTER	.002 (FATS)	.07–.28			.14
CHEESE	.009–.01				.08
GRAINS	.02–.036	.025–.035	.002–.006	.012–.048	002–.025
FRUITS (FRESH)	.004–.01	.005–.035		.018	.004–.03
EGG WHITE				.08–.125	.01
EGG YOLK				.33–.67	.062
EGG (WHOLE)	.002	.002	0		
BEER	.00007–.0014	.001–.015			.004

CONCENTRATION IN FOODS was reported by Alfred E. Stock in Germany in 1934 (*A*) and 1938 (*B*), O. S. Gibbs in the U.S. in 1940 (*C*), Y. Fujimura in Japan in 1964 (*D*) and the author's group in the U.S. in 1964 (*E*). A listing of "0" means simply a concentration too low to be detected by the method used. The World Health Organization proposed a permissible upper limit of .05 part per million for foods other than fish; the U.S. Food and Drug Administration has set an upper limit of .5 part per million for fish.

centration in the urine or in the blood has not given much enlightenment on this point. Among workers exposed to mercury in their occupations it has been found that the mercury content in the urine varies greatly from day to day and from one individual to another. As a general rule the body's excretion of mercury does tend to reflect the amount of exposure, but recent studies of workers in the chemical industries have disclosed that individuals who have been exposed to mercury in high concentrations or for long periods often show no sign of adverse effects. Furthermore, high levels in the urine or the blood do not necessarily indicate poisoning; many cases have been observed in which the individual had a mercury concentration in the blood amounting to 10 to 20 times the "normal" upper limit and yet showed no indications of illness or toxic symptoms! All in all there is substantial evidence that host factors may be more important than the amount of exposure, up to a point, in determining the individual's response to mercury in the environment. In any case, urine or blood analysis is of no value for early diagnosis of mercury poisoning. Other possible indicators, such as disturbances of the blood enzyme system, are being investigated, but no reliable diagnostic test has yet been produced. Nor can we define a precise threshold for the toxic level, either for exposure to or for absorption of mercury.

A good deal of useful information is available, on the other hand, about the sources and avenues of possible danger. Mercury in one form or another can invade the human system by way of the lungs, the skin or the ingestion of food. (Incidentally, recent studies have shown that the mercury in dental fillings is not a hazard; most people with amalgam fillings have negligible amounts of mercury in their urine or blood.) Mercury in the air, as we have noted, is a local problem confined to certain industries. Attack by way of the skin is also a problem that does not apply to the general environment, although direct contact with organic mercurials can cause severe (second degree) local burns of the skin and can result in absorption of measurable quantities of mercury into the body from underclothing and bed linen.

With regard to food, we can identify the most important possible sources of trouble. There is abundant evidence that the inorganic compounds of mercury and the phenyl mercurials are relatively nontoxic compared with the alkyl mercurials. We need to be concerned, however, about the potential conversion of the inorganic forms and the phenyls to methyl mercury, which on the basis of the experience so far must be rated as the prime hazard in the environment. A number of alkyl mercury fungicides have already been eliminated, quite properly, from use on food crops. Government agencies are now beginning to move to ban other organic mercurials as well from any use that might contaminate our food or water.

CHROMOSOME DAMAGE is found in persons with high blood levels of mercury after exposure to methyl mercury in fish. Photographs of lymphocytes made by Staffan Skerfving of the Swedish National Institute of Public Health show a broken chromosome and extra fragment (*top*) and three sister-chromatid fragments that lack centromeres (*bottom*).

A calm view of the present state of affairs regarding mercury in the environment suggests that the best way to deal with the problem is to apply the techniques of epidemiology, preventive medicine, public health and industrial hygiene that have been effective in meeting hazards in the past. A system should be set up for frequent monitoring of the environment for the detection of significant increases in mercury contamination. Research should be carried forward to establish measures for the levels and forms of mercurial pollution that signal a threat to health. Techniques for mass screening of the population to detect mercurial poisoning should be developed. Controls should be applied to stop the discharge of potentially harmful mercury wastes at the point of origin. Toxic mercurials in industry and agriculture should be replaced by less toxic substitutes. To implement such a program we shall need, of course, realistic education of the public and legislative action with adequate enforcement. And these measures should be applied to all contaminants that threaten man's environment, not only mercurials.

It would be foolish to declare an all-out war against mercury. The evolutionary evidence suggests that too little mercury in the environment might be as disastrous as too much. In the case of mercury, as in all other aspects of our environment, our wisest course is to try to understand and to maintain the balance of nature in which life on our planet has thrived.

The Detection of Gravitational Waves

The existence of such waves is predicted by the theory of relativity. Experiments designed to detect them have recorded evidence that they are being emitted in bursts from the direction of the galactic center

by Joseph Weber

The general theory of relativity predicts that accelerated masses radiate gravitational waves, that is, gravitational fields propagating with the speed of light. Such waves resemble electromagnetic waves in that they carry energy, momentum and information. Whereas electromagnetic waves interact only with electric charges and currents, however, gravitational waves interact with all forms of matter-energy.

Since 1958 I have been trying to detect such gravitational waves. For this purpose specially designed equipment has been set up in two widely separated locations: in my laboratory at the University of Maryland and at the Argonne National Laboratory near Chicago. Within the past two years simultaneous increases in the output of detectors at these two sites have provided evidence of the existence of bursts of gravitational radiation emanating from the direction of the center of our galaxy. These findings have stimulated much theorizing and a good deal of disagreement among astrophysicists. In this account I shall first describe the experiments and then summarize a few of the explanations that have been put forward for the surprising results obtained so far.

In the past new kinds of radiation were studied by producing and detecting them in the laboratory. At the time I began my experiments, however, nobody knew how to generate or detect gravitational radiation on a laboratory scale. Of course, the processes by which an atom or a molecule emits light involve the acceleration of particles with mass (electrons), and these particles should in principle generate some gravitational radiation as well. The trouble is that the ratio of electric charge to mass for an electron is extremely large. This fact, together with the small value of the gravitational constant, means that only one graviton (the quantum of gravitational radiation) would be emitted by an atom or a molecule for every 10^{43} photons (light quanta) emitted. Furthermore, the probability that an individual atom or molecule will interact with an incident graviton is extremely small, and hence detection devices based on the occurrence of such random individual interactions were out of the question.

As a result I decided at the beginning to search for gravitational radiation from very large masses—on the order of stars or galaxies—with detectors consisting of large numbers of atoms excited coherently, or as an assemblage, rather than individually. At that time no information existed regarding sources of gravitational radiation. Nonetheless, it seemed reasonable to explore possible detection techniques and start the search. Admittedly the probability of success under these circumstances had to be regarded as very small, comparable perhaps to the probability of discovering pulsars by the radio receivers available at the beginning of this century.

It was first necessary to invent a suitable gravitational-radiation antenna. I was able to show, on theoretical grounds, that gravitational waves could excite internal vibrations in an elastic solid. For there to be a resonant response the natural acoustic frequencies of the solid would have to correspond to the frequency of the gravitational waves. The center of mass of such a detector can be thought of as being in free fall under the influence of the gravitational wave; other parts of the detector would at any given moment be influenced differently by the wave and hence would be displaced slightly with respect to the center of mass, setting off internal vibrations in the solid. Detailed mathematical analysis showed that a gravitational-radiation detector built on this principle should be capable of measuring the gravitational waves (and hence the curvature of spacetime) predicted by relativity theory. What followed was the development of a completely new technology for the measurement of dynamic gravitational fields.

The sensitivity of any gravitational-radiation detector would be proportional to both its mass and its size. The largest solid mass available for use as a detector is the earth itself. The free modes of oscillation of the earth were identified in the aftermath of the great Chilean earthquake of May, 1960: typical frequencies start at one cycle every 54 minutes and range upward. To harness the earth as a gravitational-radiation detector, the acceleration of the earth's surface is recorded continuously by means of a gravimeter. A harmonic analysis is then conducted to see if some of the earth's natural frequencies are being excited. Unfortunately the earth's vibrational "background noise," resulting primarily from seismic and meteorological disturbances, is quite high. Therefore even if one were to record an excitation of one of the earth's free modes of oscillation, there would be no way of telling whether it was caused by gravitational waves or by some other natural disturbance.

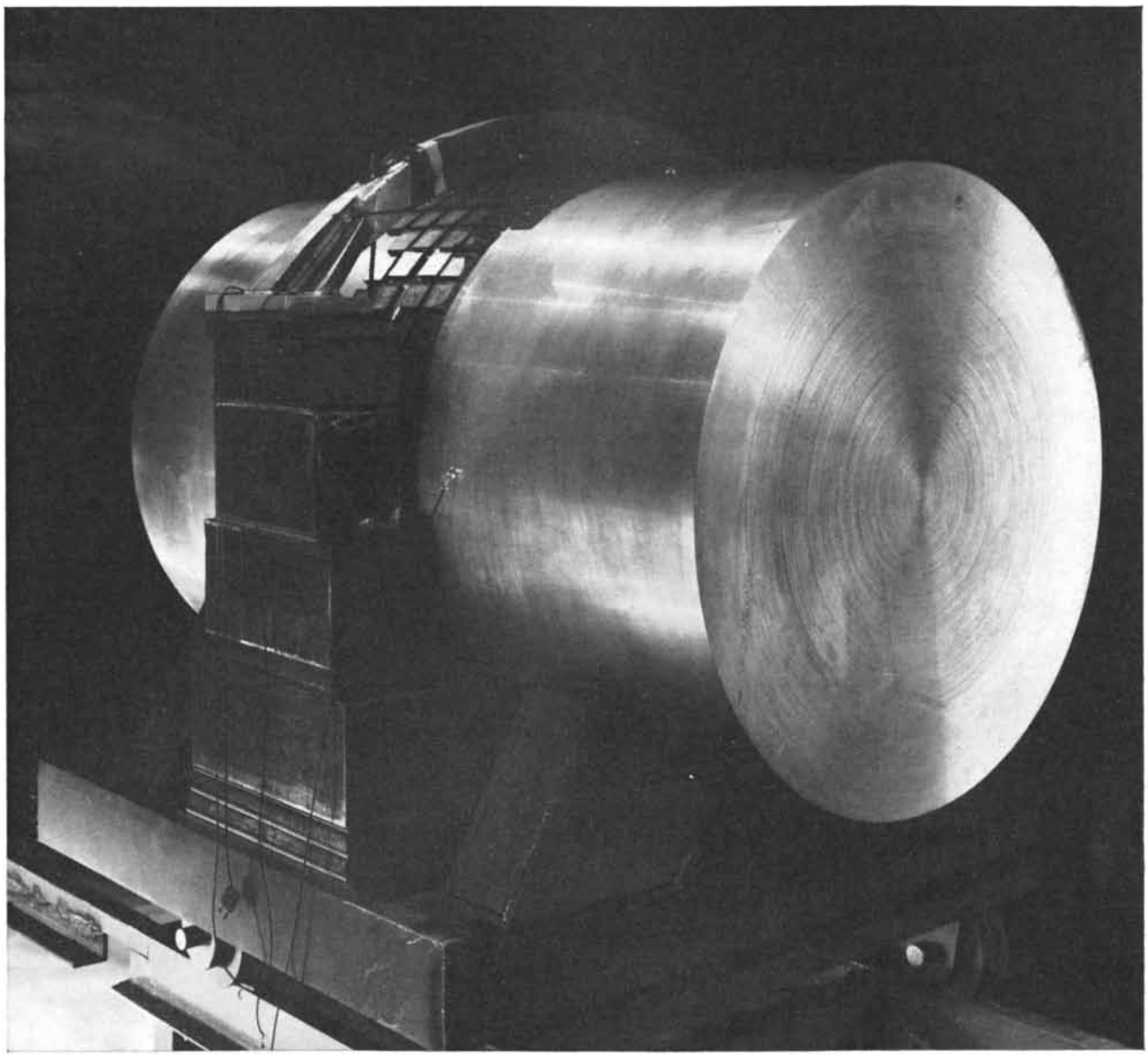
An experiment is now being developed for the National Aeronautics and Space Administration to employ the moon as such a detector. A suitable gravimeter will be placed on the lunar surface by the *Apollo 17* astronauts. The general theory of relativity predicts that certain vibrational modes with a special symmetry should interact with gravitational waves. If only these modes are found to be excited, that finding would be strong evidence for the existence of gravitational radiation at those free-oscil-

lation frequencies of the moon. For a small fraction of the time the earth is very quiet, and at such times it may be possible to observe coincident vibrations of the earth and the moon. Gravitational waves are the only known means of exciting such coincident vibrations.

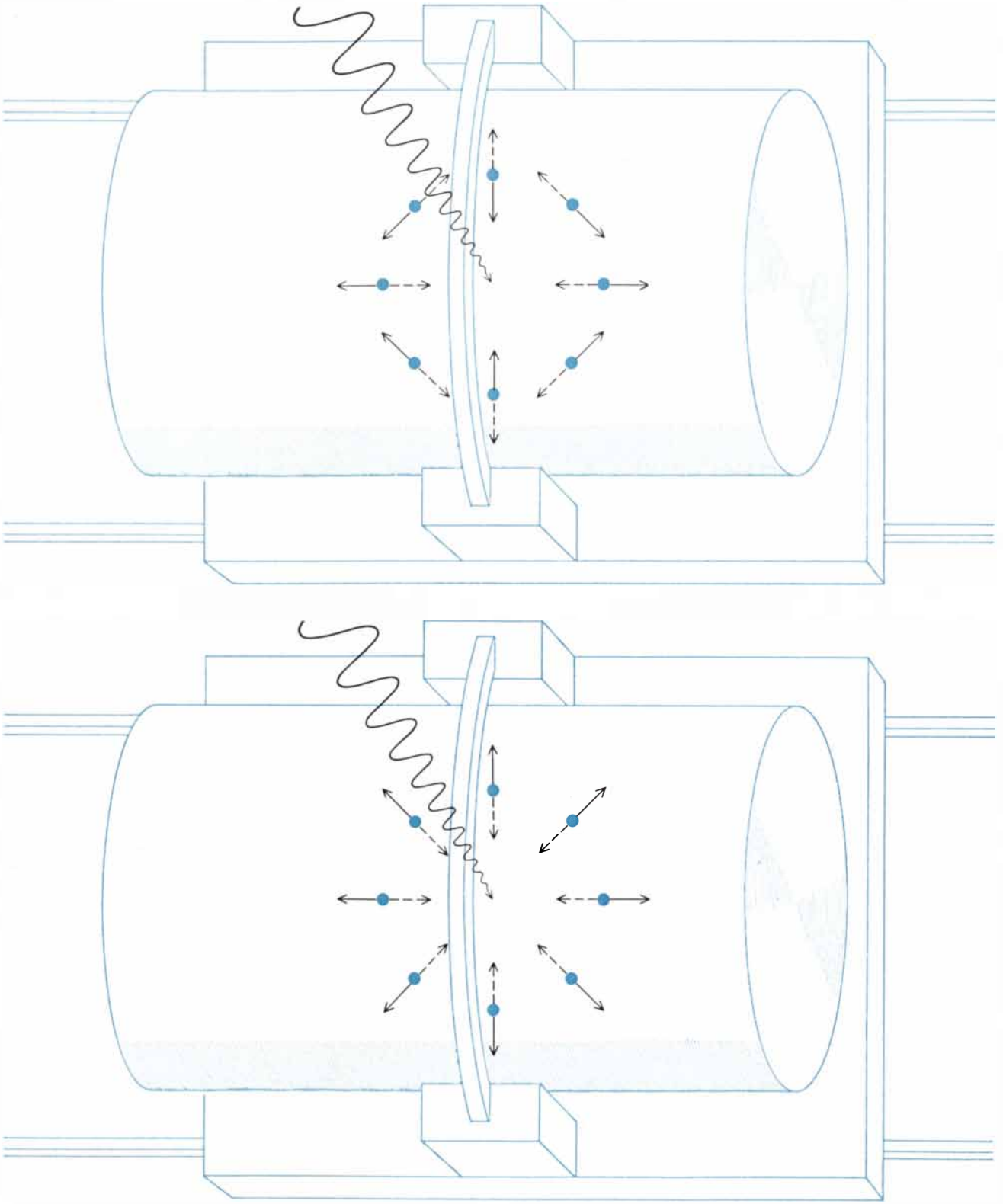
Meanwhile efforts to detect gravitational waves will continue to be limited to masses of laboratory size—on the order of tons. Such masses can to a large degree be isolated from the seismic and electromagnetic disturbances of the environment. Under those conditions the chief source of background noise is the random bombardment of the detector by air molecules.

The internal vibrations of a solid mass of this magnitude correspond to excitation frequencies on the order of one or more kilohertz (thousands of cycles per second). It turns out that this frequency range is a very promising one for investigation, because gravitational radiation in the kilohertz band would be expected from a star similar to the sun that had burned up its nuclear fuel and was undergoing gravitational collapse. If such a star originally had even a small amount of rotation, its angular momentum would be conserved until the final stages of collapse. At the same time the velocity of the star's periphery will keep increasing until the speed of light is approached. At this point the star may deform or break up, radiating away its energy and momentum in the form of gravitational waves with frequencies typically in the kilohertz region.

One of the detectors that was finally designed and built as the result of these



GRAVITATIONAL-RADIATION DETECTOR was photographed in the author's laboratory at the University of Maryland. The solid aluminum cylinder that comprises the bulk of the device measures approximately three feet in diameter and five feet in length and weighs about three and a half tons. The small blocks bonded to the surface around the middle of the cylinder are piezoelectric crystals, which generate an output voltage as a result of internal vibrations, such as those that would be excited by the passage of a gravitational wave. This experimental arrangement can sense changes in the length of the cylinder corresponding to roughly a hundredth of the diameter of the atomic nucleus. The cylinder is suspended on a steel wire strung between the two iron-block piers and is normally enclosed by a vacuum chamber. For the long-baseline coincidence experiments the system shown in this photograph is operated in conjunction with an identical detector located some 600 miles away at the Argonne National Laboratory near Chicago.



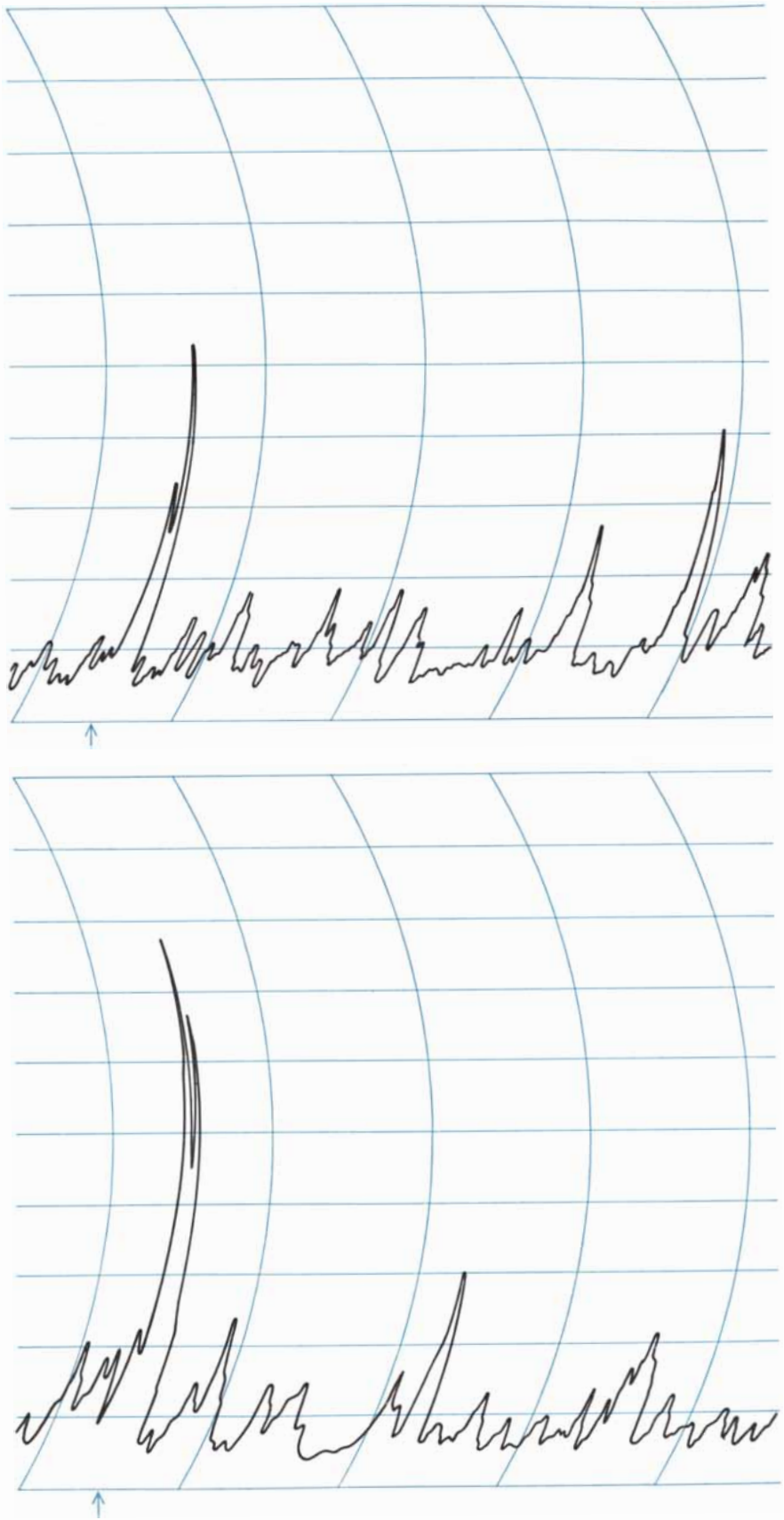
INTERNAL VIBRATIONS would be excited within a solid aluminum cylinder by an incoming gravitational wave, provided that the natural acoustic-oscillation frequency of the cylinder corresponded to the frequency of the gravitational radiation. Theoretically the gravitational radiation could be of two different types. According to the pure tensor view (*top*) the waves would excite a group of test particles (*colored dots*) inside the detector to oscillate in a complex quadrupole pattern; the solid black arrows show the distribution of forces acting on the particles at one instant, whereas the broken black arrows show the forces a half-cycle later. Such gravitational waves would have two independent states of polarization, one corresponding to the orientation of force vectors shown and the other corresponding to a 45-degree rotation of the vector pattern. According to the scalar theory of gravitation (*bottom*) an entirely different pattern of forces would be excited; the test particles would all be forced outward at one instant and inward a half-cycle later. Because the cylinders were instrumented to record internal vibrations only in the axial direction, detectors built according to this design are not capable by themselves of determining whether the observed gravitational waves are of a tensor or a scalar character.

considerations consists essentially of a solid cylinder of aluminum measuring approximately three feet in diameter and five feet in length and weighing about three and a half tons [*see illustration on page 23*]. Piezoelectric crystals (that is, crystals that respond electrically to mechanical stress) installed around the middle of the cylinder generate an output voltage as a result of internal vibrations. The sensitivity of this arrangement is such that it can record deformations of the cylinder corresponding to one part in 10^{16}, or roughly a hundredth of the diameter of the atomic nucleus for the relative displacement of the end faces of the five-foot cylinder!

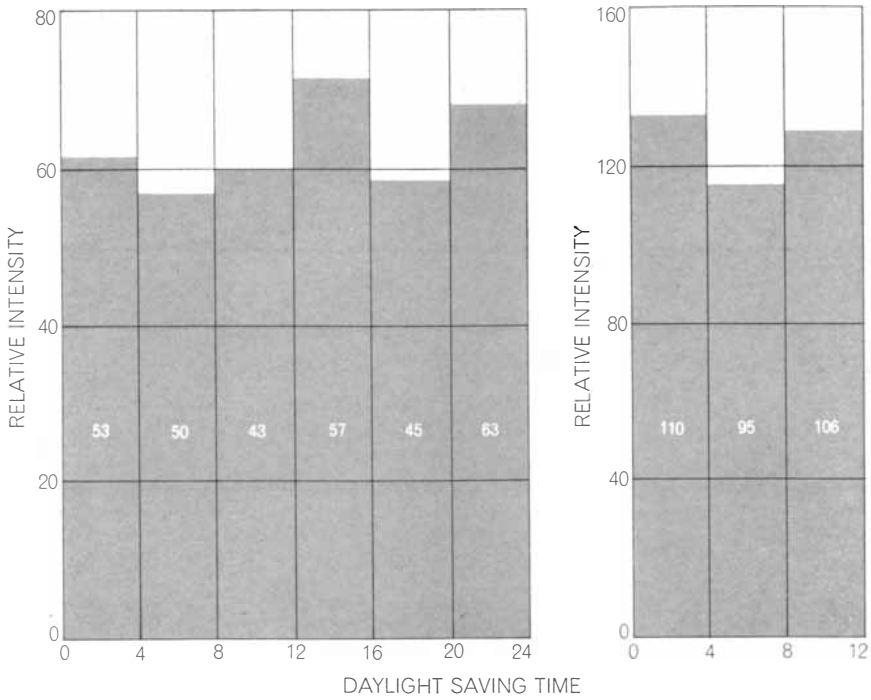
The detector is equipped with a wire suspension system and acoustic filters to shield it from environmental disturbances. To employ one detector at a time a careful study of the output noise has to be made to see if there are more large pulses than can be expected from the laws of chance. To facilitate this task it is advantageous to use two detectors in a coincidence experiment in order to search for simultaneous increases in noise output.

Even with extreme isolation measures it is impossible to protect the detectors from large disturbances such as nearby lightning strokes, the enormous magnetic fields accompanying a sudden loss of electric power or an extremely large shower of charged cosmic ray particles. Fortunately such disturbances are much less correlated at two locations that are far enough apart. Two detectors were therefore set up on a 600-mile base line with ends at College Park, Md., and at Argonne. A coincidence-recording system was developed. This is a kind of on-line computer that emits a pulse when the output of one detector crosses a threshold in the positive direction; if the output of the second detector also crosses the threshold while the first pulse is being emitted, the time overlap of the pulses creates a large voltage that triggers a coincidence marker [*see illustration at right*]. A high-quality telephone circuit with microwave relay links carries the Argonne information to Maryland in coded digital form for the coincidence experiments.

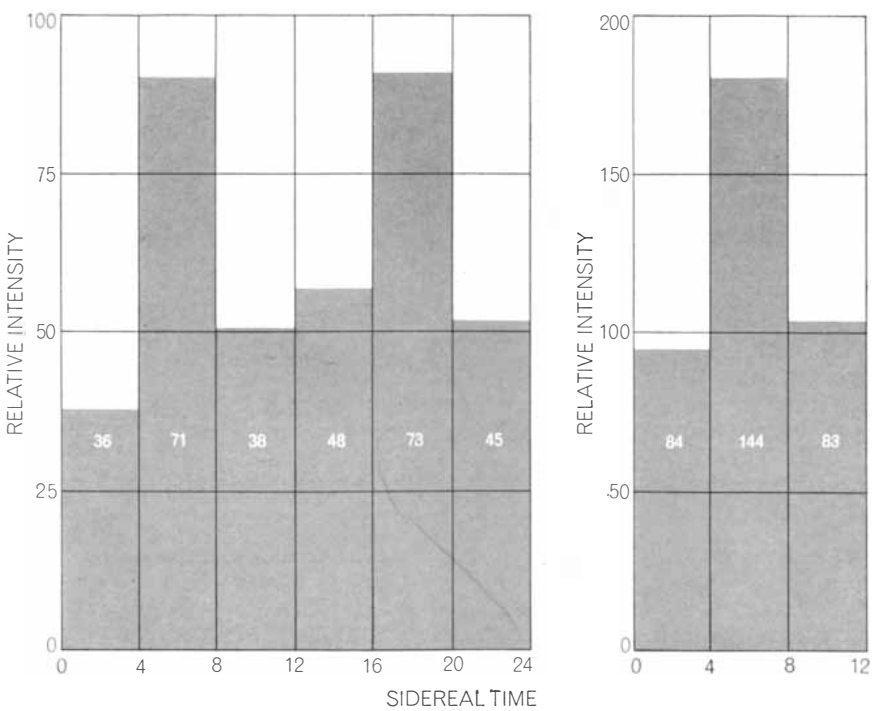
Even coincident increases in the outputs of two detectors can occur as a result of chance. A classification scheme was therefore set up for the coincidences; according to this scheme the set of amplitudes reached at each coincidence places it in a given class. For each class with a given range of amplitudes the number of chance coincidences is computed from the laws of probability.



COINCIDENCE MARKER IS TRIGGERED (*arrows*) **when the output voltages of two or more detectors cross a given threshold within a specified time interval. The trace at top represents the output of the Maryland cylindrical detector for a period of about half an hour; the trace at bottom shows the output of the Argonne cylindrical detector for the corresponding period. The time interval for defining a coincidence in this case was .44 second. The two experimental sites are connected by a special, high-quality telephone circuit.**



NO SIGNIFICANT ANISOTROPY (or dependence on direction) is revealed when the relative intensity of the observed coincidences is plotted with respect to solar time (*histogram at left*). This finding indicated that the coincidences cannot be correlated with any phenomena associated with the solar system. The numbers on the bars denote the number of coincidences in each "bin." In the histogram at right the second 12 hours is "folded" back over the first 12 hours, making use of the observed front-back symmetry of the cylindrical detectors; the larger number of events in each bin improves the statistics of the experiment.



LARGE ANISOTROPY appears when the coincidence intensity is plotted with respect to sidereal time (that is, time measured by the earth's rotation relative to the stars). The peaks in both the unfolded and the folded versions coincide with the direction of the galactic center. The one centered about 17 hours 42 minutes is associated with the meridian passage of the galactic center across the plane perpendicular to the axis of the detector. The one at five hours 42 minutes represents the galactic center again, seen through the earth 12 hours later.

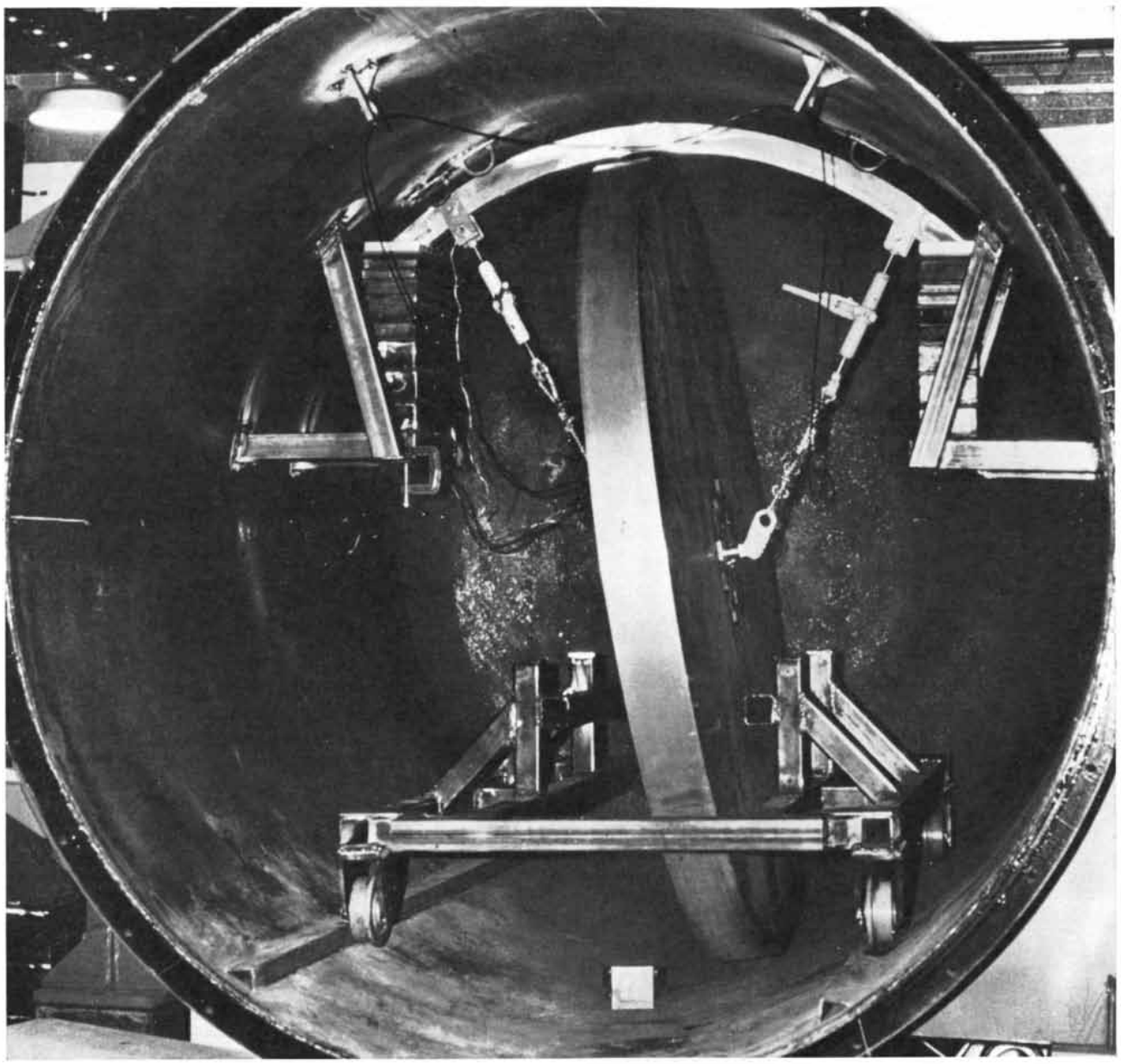
A significant excess in a given class establishes that the coincidences are not all accidental.

The validity of this procedure can be checked by noting that coincidences that are due to an external effect should disappear when a time delay is inserted in one channel. Only the chance coincidences should remain. When a time-delay experiment was done in parallel with an experiment that had no time delays, the ratio of events in the two sets of channels was five to one, indicating that without time delays five-sixths of the large-amplitude coincidences are the result of some external source, which might or might not be gravitational radiation.

In order to check the possibility that the observed coincidences might be due to nongravitational effects that somehow penetrate the acoustic filters and electromagnetic shields, further experiments were carried out. An elaborate seismic array at the Maryland site showed no correlation with the coincidences. Electromagnetic excitation proved more difficult to rule out. It is a well-known fact that kilohertz-frequency electromagnetic signals can be propagated worldwide by reflection off the ionosphere. Fluctuations in the nationwide power system might set off such signals by creating sudden large electromagnetic fields over a considerable area. In addition network television broadcasting with kilohertz modulation might, by special frequency-changing effects, excite the detectors.

Time-delay measurements proved, however, that the observed coincidences originate in the mechanical portion of the system. An even more convincing test made use of an electromagnetic receiver with a special preamplifier to enhance frequency-changing effects. The receiver was responsive to combinations of electromagnetic signals that through frequency-changing effects would give rise to the observed signals. No significant correlations were detected between such electromagnetic fields at the experiment site and the observed coincidences.

Electrical disturbances caused by intense cosmic ray showers are known to occur over small distances but not over an area as large as 600 miles. Nonetheless, my colleagues N. Sanders Wall, Gaurang Bhaskar Yodh and David H. Ezrow instrumented one of the gravitational-radiation detectors first with Cerenkov radiation counters and later with meter-square plastic scintillators, in order to check the possibility that the de-

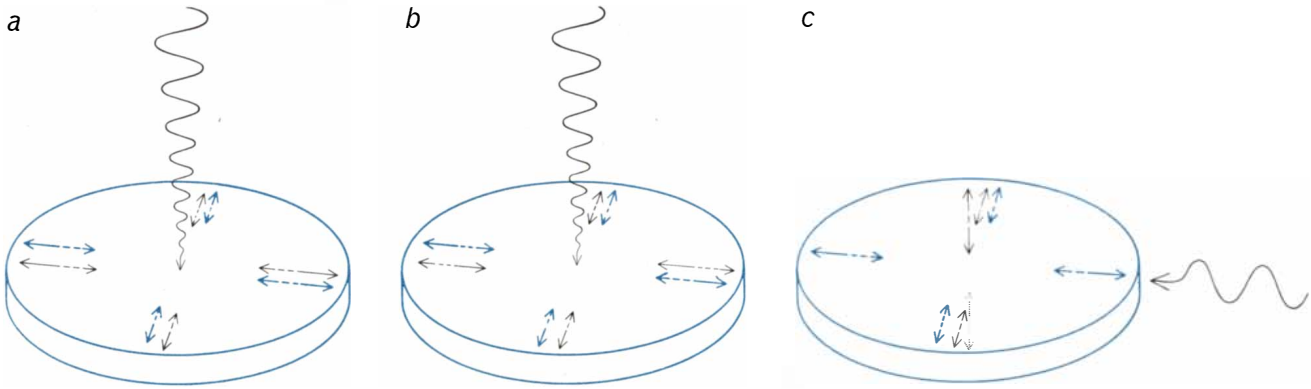


DISK-SHAPED DETECTOR was developed to help determine whether the observed gravitational radiation consists of tensor waves, as predicted by Einstein, or some combination of tensor waves and scalar waves, as proposed by some other physicists, notably Robert H. Dicke of Princeton University. The disk, consisting of about a ton and a half of solid aluminum, measures about seven feet in diameter and six inches in thickness. It is suspended inside an acoustic and electromagnetic isolation chamber at the Maryland site. For coincidence experiments, it is instrumented to operate in conjunction with a cylindrical detector at the Argonne site.

tectors were being excited by energetic cosmic ray particles. The effect of the cosmic rays was not observable in the noise.

In order to determine the direction of the source of the observed coincidences a study was made of the times at which they occurred. Since gravitational waves would not be appreciably absorbed by the earth, the directional pattern of response for a cylinder with its axis parallel to the earth's surface and pointing east and west would be expected to exhibit 12-hour symmetry. For example, if the sun were the source, intensity peaks would be expected at local noon and midnight. A comparison of coincidence intensity and solar time showed no such significant anisotropy [*see top illustration on opposite page*]. This finding demonstrated a lack of correlation of the coincidences with any phenomena associated with the solar system.

Because of the revolution of the earth around the sun the earth rotates on its axis one extra time per year relative to the stars, and a given star passes across the meridian some four minutes earlier each day. Time measured by the earth's rotation relative to the stars is called sidereal time. When the observed coincidences are plotted as a function of sidereal time, a large anisotropy appears. This is strong evidence that the gravitational radiation being received originates outside the solar system [*see bottom illustration on opposite page*]. The peaks are in the direction of the center of our galaxy. The one centered around a right ascension of 17 hours 42 minutes is associated with the meridian passage of the galactic center across the plane perpen-

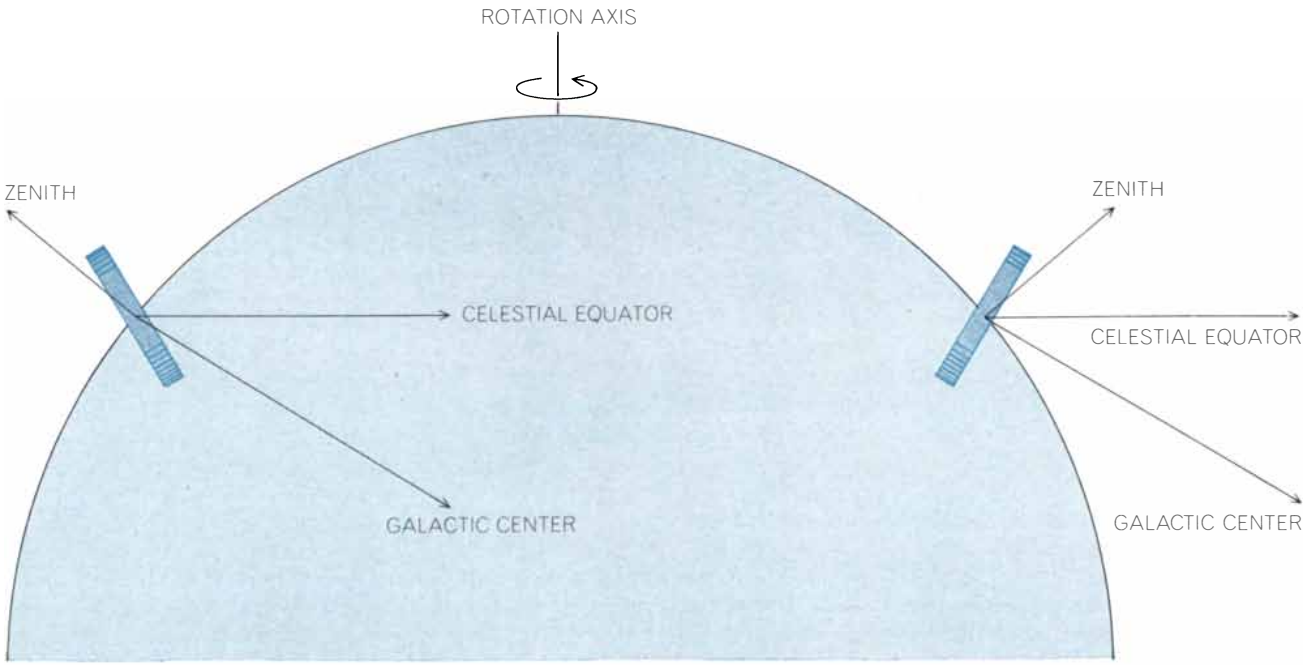


DISK IS DESIGNED TO RESONATE in the radial mode at 1,661 hertz, the frequency thought to be very likely for gravitational waves emitted from a collapsing star. This means that at some instant all the mass elements of the disk would move outward radially (*solid colored arrows*), whereas a half-cycle later they would all be moving inward radially (*broken colored arrows*). Thus a scalar gravitational wave that strikes one face of the disk along its axis of circular symmetry (*a*) would excite a resonant response in the disk, since its force vectors (*solid black and broken black arrows*) would coincide with those of the disk. A tensor gravitational wave that strikes the disk from the axial direction (*b*) would not excite the disk, because its force vectors are oppositely sensed pairs, both of which act in the plane of the disk. A tensor wave that strikes the disk edge on (*c*) would excite the disk, however, because only one pair of oppositely sensed force vectors would be in the plane of the disk, the other pair being in the thickness direction.

dicular to the axis of the detector. The peak at five hours 42 minutes represents the galactic center again, seen through the earth 12 hours later. (Gravitational waves and neutrinos are the only forms of energy that can pass through the earth with negligible attenuation, and analysis indicates that the observed directional pattern cannot be associated with neutrinos.)

Twelve-hour plots in which the second 12 hours is "folded" over the first make use of the observed front-back symmetry of the cylindrical antennas. With the larger number of events in each "bin" the improved statistics allow better comparison of theory and experiment for the ratio of center bins to end bins. The observed distribution of the events agreed nicely with the theoretical distribution computed on the assumption that the galactic center was indeed the direction of the source of the coincidences.

Einstein's theory of gravitation is a tensor theory. This means that the gravitational field at each point in space requires 10 numbers, called gravitational potentials, to describe it. One can also have a scalar theory, with one number at each point in space with a value independent of the observer's frame of reference. The tensor theory predicts waves with a quadrupole character [*see top illustration on page 24*]. A scalar wave would exhibit a completely different pattern of forces, and the forces would re-



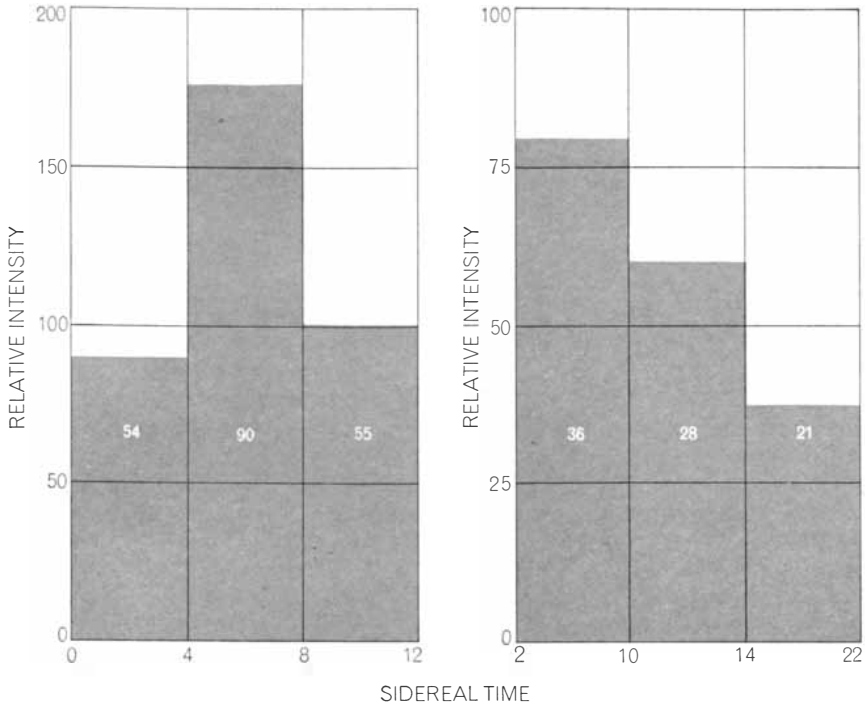
DISK IS ORIENTED with its plane facing east-west but not vertically. Thus the circular axis of symmetry of the disk is swept past the direction of the center of the galaxy at a time when the galactic center is in the local meridian (*right*). Twelve hours later, when the earth has rotated the disk 180 degrees around the polar axis, the disk "sees" the galactic center nearly edge on (*left*). If the source of the gravitational waves were in a direction exactly opposite to the direction of the galactic center, the same results would be obtained.

verse their sign every half-cycle [*see bottom illustration on page 24*]. Various physicists, notably Robert H. Dicke of Princeton University, have proposed modifications of Einstein's theory in which there is a mixture of scalar and tensor forces. It was thus of interest to investigate the character of the gravitational radiation being observed. For this purpose a special disk-shaped antenna was developed [*see illustration on page 27*].

If scalar gravitational waves exist, their arrival from the direction of the axis of circular symmetry of the disk will excite the disk's radial modes of oscillation; tensor waves from that direction will not excite the radial mode because one pair of tensor forces would cancel the effect of the other pair. The tensor wave can excite the disk only if the wave meets the disk nearly edge on [*see top illustration on opposite page*]. In this case one pair of forces will excite the radial mode and the oppositely sensed pair will act in the thickness direction and will not produce cancellation.

The experiment was set up with the plane of the disk pointing east-west but not vertically. For that orientation the axis of symmetry of the disk was swept past the galactic center when the galactic center was at the meridian. The symmetry of the disk is different from the symmetry of the cylinder, however. When the earth has rotated the disk 180 degrees around the polar axis, the disk "sees" the galactic center nearly edge on [*see bottom illustration on opposite page*]. The disk was operated in coincidence with a cylinder at the Argonne site at the same time that the two cylinders were operated in coincidence.

For the two cylinders the front-back symmetry again was utilized, and the second 12 hours of sidereal time was folded over the first. Again the sidereal anisotropy was reproduced, with large peaks in the direction of the galactic center [*see illustration on this page*]. Since the disk experiment does not have 12-hour symmetry, right-left symmetry of the disk is utilized in plotting the histogram. The sidereal time sector from 14 to 22 hours corresponds to the disk's symmetry axis pointing at the galactic center. The sector from two to 10 hours is the nearly edge-on situation where a maximum is expected for the tensor field. The remaining sectors are combined in the center bin. The disk-cylinder coincidence intensity is seen to be characterized by a hole in the direction of the galactic center, corresponding to an absence of a scalar component, in agreement with Einstein's pure tensor theory. It must be pointed out, however, that a scalar component smaller than a few percent could not have been detected.



RESULTS of the experiment in which the disk at the Maryland site was operated in coincidence with a cylinder at the Argonne site at the same time that the two cylinders at the two sites were operated in coincidence are presented in these histograms. For the two cylinders (*left*) the second 12 hours of sidereal time is again folded over the first. As before, the sidereal anisotropy appears, with large peaks in the direction of the galactic center. Since the disk-cylinder experiment (*right*) does not have 12-hour symmetry, right-left symmetry of the disk is made use of in plotting these bars. The sidereal time sector from 14 to 22 hours corresponds to the disk's symmetry axis pointing at the galactic center; the sector from two to 10 hours is then the nearly-edge-on situation where a maximum is expected for the tensor field. The remaining sectors are combined in the center bin. The "hole" in the direction of the galactic center observed in the disk-cylinder coincidence intensity suggests the absence of a scalar component, in agreement with Einstein's pure tensor theory of gravitation.

The experimental facts are now unequivocal. If we assume that the experiment is observing gravitational radiation from the galactic center and that the analysis of the sensitivity of the detector is correct, each event corresponds to an amount of energy being radiated by the galactic center that equals roughly a fifth of the mass of the sun, that is, an amount equivalent to the conversion of a fifth of the sun's mass into energy. Allowing for the small detection efficiency, it corresponds to an energy of perhaps 1,000 solar masses per year or more. This is a stupendous amount of energy, more than 10,000 times greater than all the light waves and radio waves emitted from the direction of the galactic center. Dennis W. Sciama, Martin J. Rees and George B. Field have noted that existing knowledge of the dynamics of our galaxy is not inconsistent with an energy loss of perhaps 200 solar masses per year. Their arguments are based on the observed recession of stars, which could be explained on the basis of a loss of gravitational binding energy. Furthermore, Sciama finds that there are no stars in bound orbits with periods exceeding a billion years, a fact consistent with a large loss of galactic mass.

The origin of the observed gravitational radiation has not been determined, only the direction of its arrival. It is conceivable that the source might be an unusual object such as a pulsating neutron star very much closer than the galactic center. It is also conceivable that the mass at the galactic center is acting as a giant lens, focusing gravitational radiation from an earlier epoch of the universe. Since gravitational radiation is not appreciably absorbed by matter, it should have been accumulating since the beginning of time. The relatively large intensity apparently being observed may be telling us when time began.

THE OLDEST FOSSILS

The remains of ancient bacteria and algae, some of them more than three billion years old, have been found in Africa, Australia and Canada. They provide evidence on the earliest stages of evolution

by Elso S. Barghoorn

How did life originate on the earth? It was not so long ago that attempts to answer this question defined more areas of uncertainty than of agreement. Today a fossil record that was virtually unknown before the 1950's has been found to bear witness to three of the key events in the earliest stages of organic evolution. The fossils come from widely separated parts of the earth. All are preserved in unusual rocks of the Precambrian, the first and by far the longest interval in geologic history. The earliest of the fossils are more than three billion years old.

All that is known or conjectured about the terrestrial origin of life suggests that the first appearance of living organisms was preceded by the gradual development of a complex chemical environment. This environment is usually pictured as a kind of primordial broth, filled with such "organic" molecules as amino acids, sugars and other biologically important substances that came into existence through nonorganic processes. Millions of years must have been required for the accumulation, elaboration and differentiation of the broth. That period may be called the time of chemical evolution, a concept that owes much to the work of a leading student of abiotic synthesis, Cyril A. Ponnamperuma of the Ames Research Center of the National Aeronautics and Space Administration. As a preliminary stage in the total process of organic evolution, chemical evolution of course reaches its climax when lifeless organic molecules are assembled by chance into a living organism. This first form of life is what the Russian biochemist A. I. Oparin calls a "protobiont."

Judging from the various forms of life we know today, the first protobionts were probably microscopic in size and single-celled in structure, perhaps resembling the modern coccoid, or spherical, bacteria. Rather than imagining some specific organism, however, let us consider this first form of life more abstractly and give it a name that describes how it lives rather than how it looks. Call it a heterotroph, which is to say an organism that cannot manufacture all its own nutrients but must feed on organic molecules in the broth that surrounds it. (This assumes that the organism is immersed in an aqueous medium or at least rests on a wet surface; a supply of water is essential to protoplasmic life.) It seems reasonable to suppose that the organism was a heterotroph; to have at this stage a full-fledged autotroph, an organism that can manufacture its organic nutrients out of inorganic substances, would be asking too much of chance.

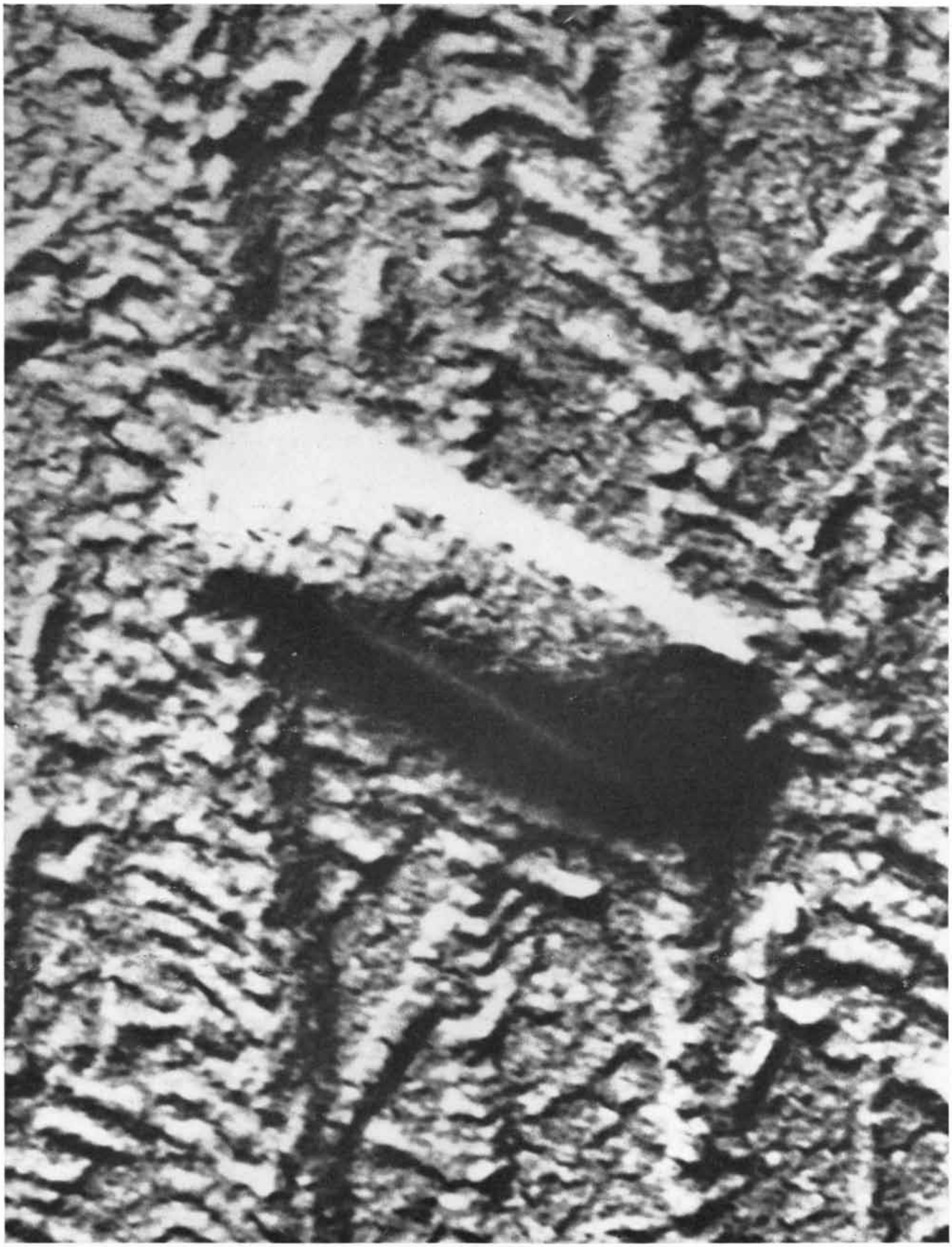
We can, however, demand that heterotrophs rather promptly give rise to autotrophs. Otherwise, as Preston Cloud of the University of California at Santa Barbara puts it, once the heterotrophs had "gobbled up all the goodies" within reach they would die off, making another accident of biosynthesis necessary in order to get things going again.

One way or another, then, autotrophs must evolve from an original heterotrophic population. This event in the development of life marks the time when the organic nutrients of the primordial broth are depleted and photosynthesis—the most plausible form of organic self-nutrition—must have been invented. Such an assumption is not based solely on logical considerations of thermodynamics and physiology. It is also supported by geological evidence that early organisms depended on photosynthesis to sustain themselves. Among the most ancient formations in the geological record are some showing signs that small amounts of free oxygen—the gaseous by-product of photosynthesis—were present early in the history of the earth. This chemical evidence coincides with indications in the fossil record that some of the most primitive forms of terrestrial life, organisms that resembled modern bacteria and blue-green algae, were then increasing in numbers and diversity.

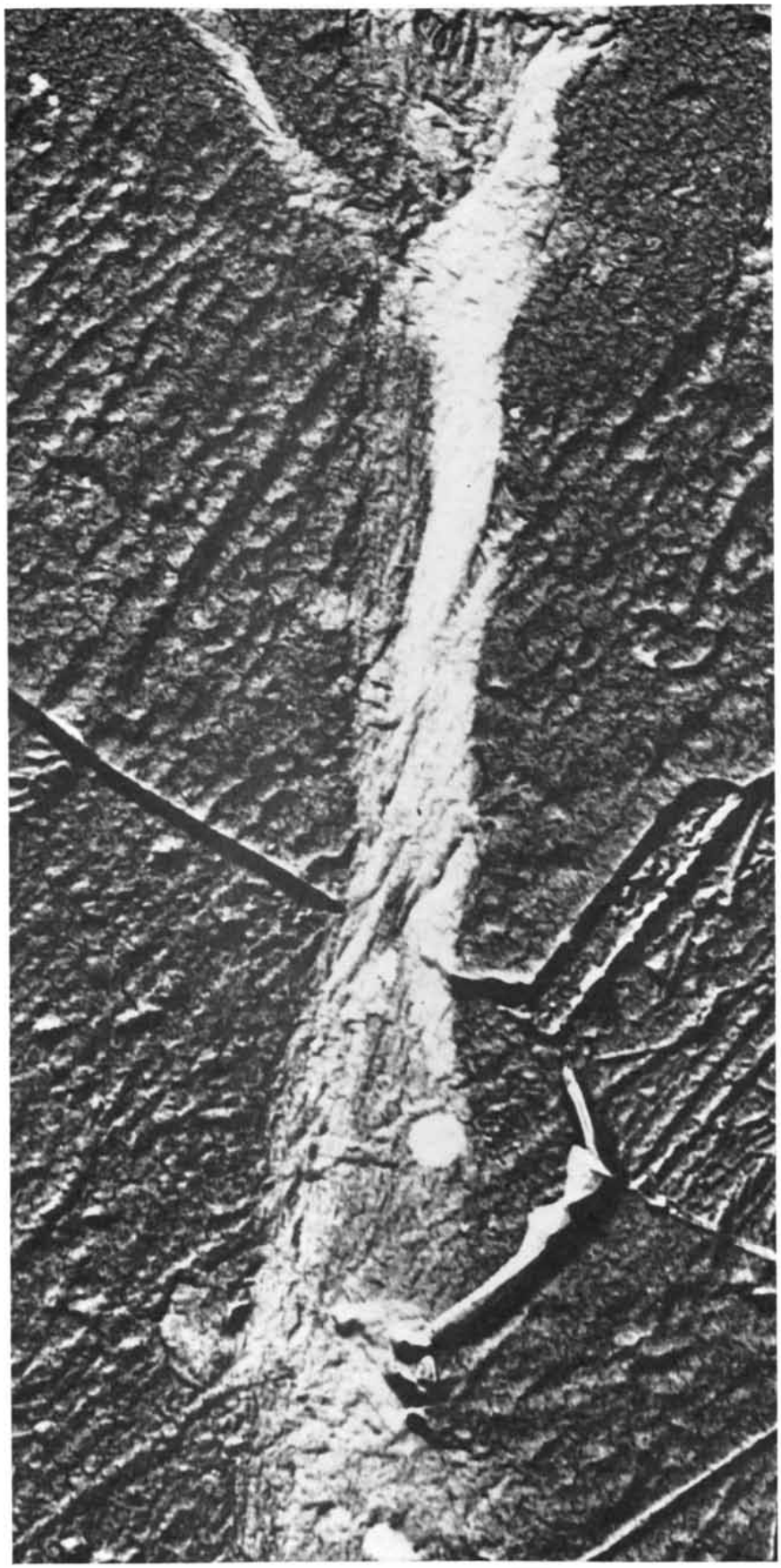
Many modern bacteria are photosynthetic, although they do not produce free oxygen; all modern blue-green algae are photosynthetic and all produce free oxygen. The evidence suggesting that the first autotrophs were organisms of the same primitive kind is significant for an additional reason. Bacteria and blue-green algae are alone among living things in the simplicity of their cells. They have neither a cell nucleus nor such specialized cellular organelles as mitochondria and ribosomes. Both are essentially sexless. Their genetic material is diffused throughout the cell, and they are incapable of either mitosis (body-cell division) or meiosis (germ-cell division). Both kinds of cell division require that the genetic material be organized into chromosomes.

Bacteria and blue-green algae are thus fundamentally different from other organisms: all other plants, all animals and the many forms that are neither entirely plant nor entirely animal. These other organisms have cells with nuclei and specialized organelles or specialized intracellular structures; they are called eukaryotic (truly nucleated), whereas bacteria and blue-green algae are prokaryotic (prenuclear). It would be surprising if the autotrophs on the lowest rungs of the evolutionary ladder were anything but prokaryotic.

The prokaryotic cell is notable for still another reason. Any organism whose genetic material is diffused throughout the



OLDEST KNOWN BACTERIUM, one of two primitive forms of life preserved in a Precambrian rock formation in South Africa, appears as a raised rectangular shape in this electron micrograph. What is seen is a carbon replica of the polished surface of a rock sample, shadowed with heavy metal. The fossil bacteria come from cherts of the Fig Tree formation; they are from .5 to .75 micron long and about .25 micron wide. The organisms are some 3.2 billion years old and have been given the name *Eobacterium isolatum*.



THREADLIKE FILAMENT of organic matter resembling decomposed plant tissue is another kind of fossil that appears in electron micrographs of the Fig Tree cherts. Some specimens are nine microns long. Not identifiable with any known organism, the filaments might conceivably be polymerized abiotic molecules from the "primordial broth."

cell and whose reproduction does not involve a recombination of parental genes is genetically conservative. In such an organism random mutations, instead of being preserved when they benefit the organism, tend to be damped out in a few generations. The blue-green algae are an outstanding example of such genetic conservatism. Many living species are almost indistinguishable in structure from species that flourished a billion or more years ago.

Against this background of fact and conjecture, how many of the events in the early stages of organic evolution can be labeled as being outstanding? There appear to be three such events, each of them a kind of threshold-crossing. The first, obviously the *sine qua non*, is successful biosynthesis: a crossing of the threshold separating the initial period of abiotic chemical evolution from the subsequent organic period. Perhaps someday fossil evidence of the earth's earliest organisms, the heterotrophs that crossed this first threshold, will be discovered. In the meantime the remains of their successors, the early photosynthetic autotrophs, provide the necessary proof that the first threshold had been passed.

The next threshold can be characterized as the threshold of diversification. As evolution progresses the first photosynthetic organism should not be limited to a few similar forms. Instead they should develop differences in shape and structure indicative of roles in a variety of ecological niches.

The third threshold divides prokaryotic organisms from all others. A world populated solely by bacteria and blue-green algae is conceivable; indeed, that is apparently the way it was. Viewed from our present vantage such a world seems poor in possibilities for further evolution. The extraordinary variety of plant and animal life that has arisen on the earth over the past 600 million years is due entirely to the invention of the eukaryotic cell, with its potential for genetic diversity.

Thanks to a lucky accident of fossil preservation, we now have evidence that each of these thresholds was successfully crossed during the vast span of Precambrian times. The Precambrian represents nearly four billion of the earth's first 4.5 billion years. It began with the formation of the earth and ended some 600 million years ago with the dawn of the Paleozoic era [*see illustration on page 41*]. Nothing is known of the first billion years or so; the world's oldest-known rocks, found in Africa, are not

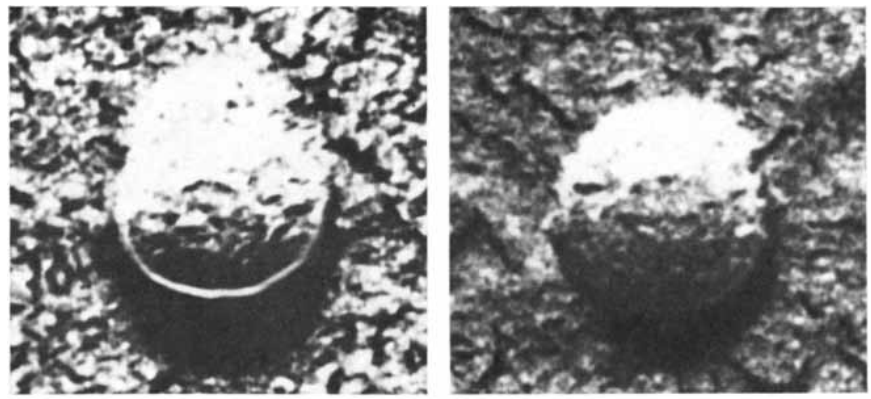
much more than three billion years old.

Precambrian rocks are found not only in Africa but also on every other continent. The best-known areas are the Canadian Shield in North America and the Fenno-Scandian Shield in Europe, but more than a third of Australia is also a Precambrian shield and there are sizable Precambrian areas in South America and Asia. Some Precambrian rocks are of igneous origin and some are of sedimentary origin. Most of the sediments have been heavily metamorphosed: changed in form and chemical composition by heat and pressure. In these metamorphic rocks not only fossils but also the faintest traces of organic matter have been obliterated.

A few Precambrian sediments have escaped substantial alteration. Extensive deposits of black shale, black chert and other stratified sediments are scattered through the major shield areas in virtually unmetamorphosed condition. These carbon-rich rocks—for example the formations in the Lake Superior region of North America, in the Transvaal of South Africa and in parts of western Australia—look even to the experienced eye very much like certain sediments of the Carboniferous epoch that are a mere 300 million years old.

The oldest-known group of Precambrian sediments is located in the border region between the Republic of South Africa and Swaziland. The formation is called the Swaziland Sequence; its stratified rocks are thousands of feet thick. One series of strata in the middle of the sequence, known as the Fig Tree formation, is well exposed in the Barberton Mountain Land, a gold-mining district near the town of Barberton in the eastern Transvaal. The Fig Tree rocks consist of black, gray and greenish cherts, interbedded with jaspers, ironstones, slates, shales and graywackes. In places the chert beds are 400 feet thick. The chert is usually fractured, but it is cemented together and the fractures are filled with quartz; parts of the formation show little evidence of metamorphism. The Fig Tree cherts contain traces of organic matter and a few microfossils.

The Barberton Mountain Land has long been an active mining area, and its geology has been studied in considerable detail. The age of the graywackes and shales has been determined independently by several laboratories using a method based on the decay of radioactive strontium and rubidium. This particular radioactive clock started to run 3.1 billion years ago, but there is good reason to believe the sediments were deposited somewhat earlier. Recently rocks lying close to the base of the Swaziland Sequence (and thus well below the level of the Fig Tree cherts) were shown to be 3.36 billion years old. In light of these age determinations it seems probable that the age of the Fig Tree cherts is in excess of 3.2 billion years.

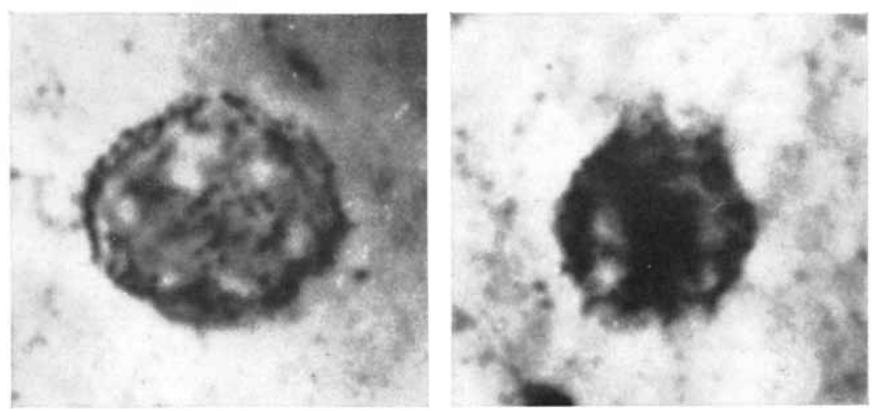


TWO CROSS SECTIONS of *Eobacterium* are seen in electron micrographs of metal-shadowed carbon replicas. In the fossil at left the outer and inner layers of the cell wall are visible. The wall, .015 micron thick, resembles the wall of living bacteria of the bacillus type.

In 1965 I collected cherts from several localities in the Fig Tree series, and samples were prepared for examination in my laboratory at Harvard University that summer. Two techniques were employed: thin sections of chert were cut for examination by reflected and transmitted white light under the microscope, and carbon replicas of etched and polished chert surfaces were made. The carbon replicas were then "shadowed" with metal and examined by transmission electron microscopy. J. William Schopf joined me in the study of the specimens.

When Schopf and I examined the thin sections under the light microscope, we could see that the rock matrix contained abundant laminations of dark-colored and virtually opaque organic matter. The laminations were irregular but were usually aligned parallel to the strata of the chert, suggesting that they had originally been formed as part of an aqueous sedimentary deposit. No distortion was evident where the organic matter crossed the boundaries of the individual grains of chalcedony comprising the chert, which suggested to us that the process of deposition had emplaced the organic material within a silica-rich matrix before the silica was crystallized into chert. There was no evidence whatever that the silica was of secondary origin.

It was difficult to discern distinct bodies within the layers of organic matter under the light microscope. Our first success in isolating a Fig Tree organism was achieved with the carbon-replica technique; the electron microscope revealed a number of rod-shaped structures, preserved both in profile and in cross section. The rods are very small. They range in length from slightly under .5 micron to a little less than .7 micron, and in diameter from about .2 micron to a little more than .3 micron. In cross section the cell wall is sometimes seen to



ALGA-LIKE SPHERES, seen in photomicrographs of thin sections of rock, are the other fossil organisms that are found in the Fig Tree formation. The diameter of the spheres is usually less than 20 microns. The organism is named *Archaeosphaeroides barbertonensis*.

consist of an inner and an outer layer, with a total wall thickness of .015 micron [*see top illustration on preceding page*]. This is comparable to the cell wall of many modern bacteria in both structure and dimension.

Electron microscopy also revealed the presence of organic material in the form of irregular, threadlike filaments lacking discernible structural detail. The threads are clearly native to the chert and not the products of contamination. They are as much as nine microns long and resemble decomposed plant material. Although these filaments are almost certainly of biological origin, they cannot be identified with any known type of organism. It has been suggested, probably as a result of wishful thinking, that they may be polymerized strands of abiotic organic matter from the primordial broth.

Schopf and I later succeeded in resolving larger microfossils in thin sections of Fig Tree chert under the light microscope. These fossils are spheroidal; measurements of 28 particularly well-defined specimens show that the majority are between 17 and 20 microns in diameter [*see bottom illustration on preceding page*]. Some have a darkened interior, as if cytoplasm within the spheroid had coalesced and become "coalified." Just as the rod-shaped organisms revealed by the electron microscope resemble certain modern bacteria, so the spheroids are not unlike some modern blue-green algae of the coccoid group. They may even be among the evolutionary precursors of such algae.

We have named the rods *Eobacterium isolatum,* a new genus and species. The generic name (*eo-* is the Greek root for "dawn") points to the great antiquity of the organism and to its bacterium-like appearance; the specific name defines its noncolonial, single-cell habit of growth. The spheroids we have named *Archaeosphaeroides barbertonensis,* also a new genus and species. Again the generic name refers to the organism's great age and its appearance; the specific name identifies its place of discovery. The existence of these two organisms, successful inhabitants of an aquatic environment more than three billion years ago, is evidence that the first evolutionary threshold—the transition from chemical evolution to organic evolution—had been safely crossed at some even earlier date. We now know that at least two living organisms appeared well before the first third of earth history had passed. If we accept the evidence (to which we shall return) that the alga-like Fig Tree organisms were photosynthetic, an important geochemical event must also have occurred. With the onset of photosynthesis free oxygen would have begun to appear among the other constituents of the environment. The appearance of free oxygen was an event destined to have profound influence, both biological and geological, on the subsequent history of the earth.

Evidence of the second evolutionary threshold-crossing comes from North America. A remarkable outcropping of Precambrian rocks along the shore of Lake Superior in western Ontario shows a sequence of sediments known as the Gunflint Iron formation. The rocks at the base of the Gunflint formation include beds of black chert three to nine inches thick. The beds are exposed—in some places more or less continuously and in others as isolated outcrops—over a distance of some 115 miles in Ontario, from the vicinity of Schreiber on the east to Gunflint Lake on the west. Like the much earlier Fig Tree series, the Gunflint formation has been the subject of detailed geological investigation.

Granite underlies the Gunflint formation unconformably, that is, the basement rock had been eroded before the Gunflint sediments were deposited on its surface. Radioactive clocks have yielded two independent dates for the granite. A concentrate of its biotite contents indicates an age, in terms of the argon-potassium ratio, of 2.5 ± .75 billion years. The age of a whole-rock sample, in terms of its rubidium-strontium ratio, is 2.36 ± .70 billion years. The age of the granite thus provides a "floor" of maximum age under the Gunflint formation. The Gunflint cherts cannot be any older than these dates.

Micas separated from rocks in the upper levels of the Gunflint formation, collected near Thunder Bay, indicate an age in terms of the argon-potassium ratio of 1.60 ± .05 billion years. For technical reasons this figure is only 80 percent of the true age; it must therefore be adjusted to 1.90 ± .20 billion years. The micas thus provide a "ceiling" of minimum age for the cherts that lie at the base of the Gunflint formation. It seems reasonable to set the age of the cherts at approximately two billion years, which makes them a billion years or so younger than the Fig Tree cherts.

The only rocks in the Gunflint formation that contain microfossils are the cherts. Like the Fig Tree cherts, they are evidently the product of deposition in an aqueous environment that was rich in silica. Most of the Gunflint fossils are three-dimensional, and many show exquisite anatomical details. It has been argued that the structure of these fossils has been preserved by the infiltration of silica from the surrounding sediments. In my opinion the organisms were preserved without distortion by being deposited in a siliceous solution that later crystallized into chert, much as a modern biological specimen is preserved by being embedded in plastic. The soft structure of the organism owes its preservation to the almost complete incompressibility of the silica matrix. This is as unusual as it is fortunate. In most instances of fossil preservation the matrix is composed of relatively plastic sediments that are much compressed during consolidation, with the result that any preservation of soft tissues, let alone preservation in three-dimensional form, is a rarity.

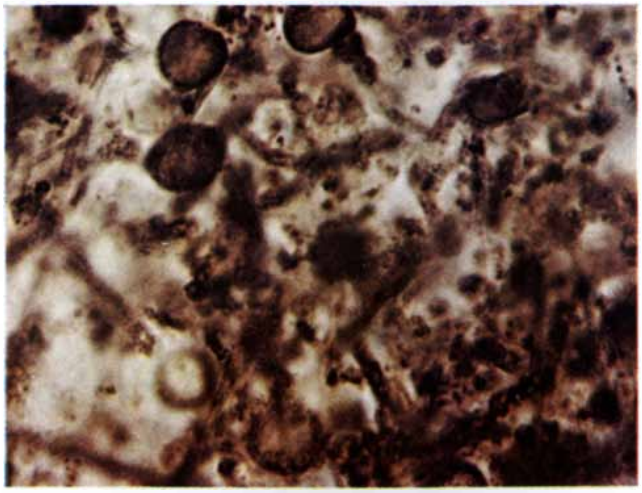
How were the Gunflint cherts deposited? The picture in Ontario is rather clearer than it is in the Transvaal. The Gunflint cherts were apparently precipitated and consolidated around an underlying complex of basement rocks, consisting of greenstone boulders and finer conglomerates, that seems to have been continuously submerged at the time. "Domes" of algae, which are visible to the unaided eye in samples of Gunflint rock, grew on the surface of the boulders. Algal "pillars" grew perpendicularly to the domes; their fossil remains consist of alternate layers of coarsely crystalline quartz and fine-grained black chert [*see bottom illustration on opposite page*].

In the 1950's I was privileged to be associated with Stanley A. Tyler of the University of Wisconsin in collecting and analyzing specimens of Gunflint chert from the Schreiber area. Only a few preliminary studies of these and other Gunflint specimens were published before Tyler died, although by then we both knew that his work had added to the fossil record an entire new group of very ancient, primitive photosynthetic organisms whose existence had not been suspected. Indeed, even though many years of study have now been devoted to the Gunflint organisms, the formation continues to yield new finds. Eight genera of primitive Gunflint plants, comprising 12 species, have been described so far, yet accompanying this article are illustrations of new forms of undetermined taxonomic status.

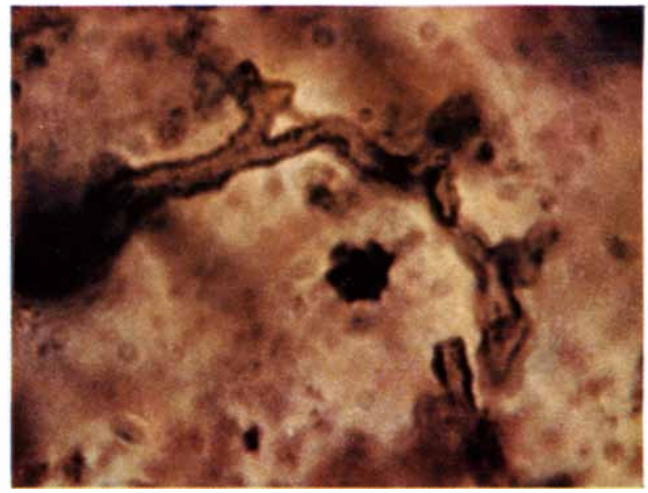
The most abundant of the Gunflint microfossils are filamentous structures. The majority of them are between .6 micron and 1.6 microns in diameter but a few are more than five microns across. They vary in length up to several hundred microns. Some of the filaments have inter-

SAMPLE OF GUNFLINT CHERT of Ontario (*above*) has a knobby surface. The knobs, exposed by weathering, are tops of pillars formed by algae in shallow water where Gunflint organisms lived.

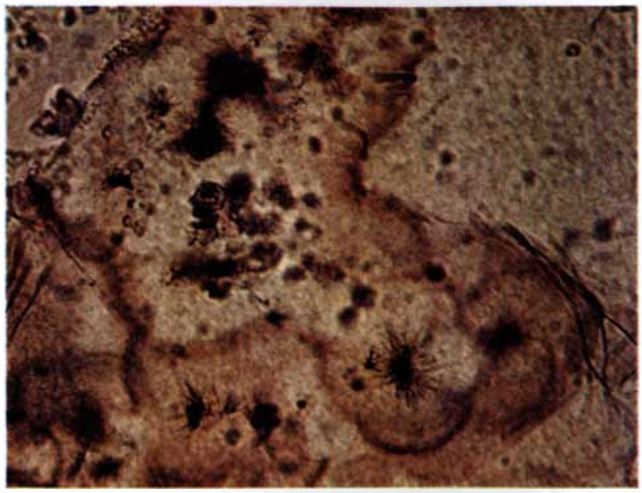
VERTICAL SECTION through a chert sample (*below*) shows the structure of the algal pillars. Layers of quartz and of fossil-bearing black chert alternate in each pillar like sets of nesting thimbles.



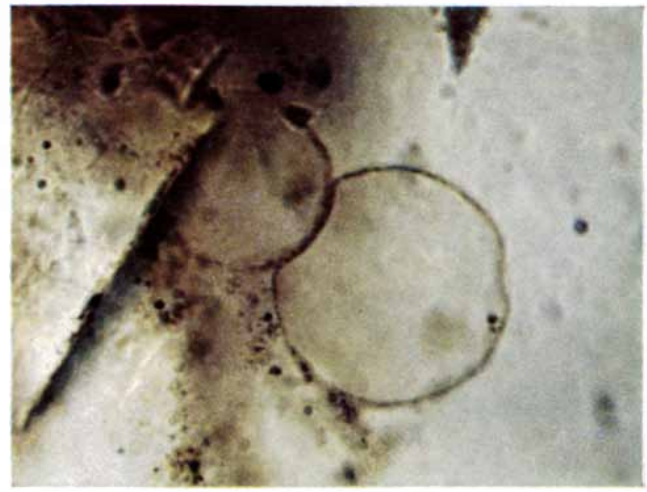
DENSE MIXTURE of organic detritus, spherical bodies and filaments is enlarged 250 diameters in this photomicrograph. All the micrographs on this page show thin sections of the Gunflint cherts.



TUBULAR FILAMENT with branches and swellings is not obviously related to any living organism. Where it is not swollen it is about two microns across. It is called *Archaeorestis schreiberensis.*



COLONY OF ALGAE is enlarged 200 diameters. The organisms, each a cluster of spikelets, have been named *Paleorivularia ontarica* because of their resemblance to the living genus *Rivularia.*



CLOSE CONTACT between a larger and a smaller cell is apparent in a chert section enlarged 1,000 diameters. Interrelations of this kind may represent a stage in the evolution of the eukaryotic cell.

SPHERE WITHIN SPHERE, the inner one held away from the outer one by a number of smaller spheroids, is about 30 microns in diameter. The spheres comprise the extinct species *Eosphaera tyleri.*

ASYMMETRICAL CELL, found in a recently prepared chert section, has not yet been formally classified. The Gunflint cherts have been studied for nearly 20 years, but they still yield new organisms.

nal walls at right angles to their length; others lack such walls. Where the walls are present, they can be broad or narrow. These primitive plants have been assigned on the basis of their morphology to four genera including five species. Among the present-day blue-green algae they resemble are the filamentous *Oscillatoria* and related forms; one of the four also shows resemblances to the modern iron-oxidizing bacterium *Crenothrix*.

Another genus of Gunflint organisms is represented by small spheroids, ranging from one micron in diameter to more than 16 microns. The walls of the spheroids vary both in thickness and in structural detail. Because of these variations they have been assigned to three separate species and placed in the genus *Huroniospora*. The spherical organisms are found in chert collected from many parts of the Gunflint formation but they are not equally abundant everywhere.

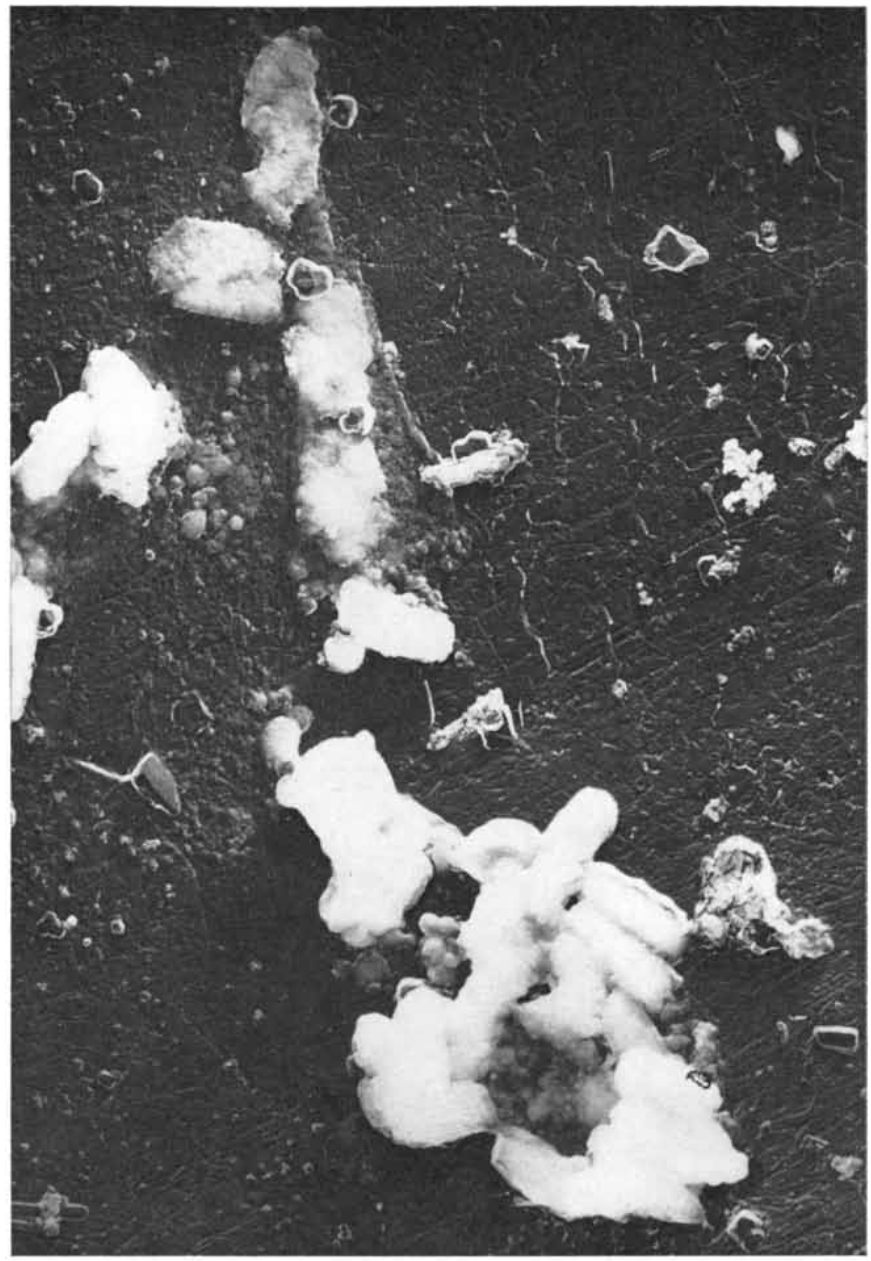
What kinds of organism are represented by the spheroids? We have only their simple morphology to judge by. Like their counterparts in the much older Fig Tree cherts, they might be noncolonial blue-green algae of the coccoid group. They might also, however, be the reproductive spores produced by the filamentous plants mentioned above, and some might even be the spores of iron bacteria. Still another possibility is that they are the fossilized bodies of free-swimming organisms whose flagella have not been preserved. Further study may lead to a choice among these alternatives.

The remaining Gunflint genera that have been intensively studied and described so far all show unusual characteristics. The organisms in one of the three genera are star-shaped and made up of radially arrayed filaments. The diameter of the "star" ranges from eight to 25 microns; in rare cases some of the filaments are branched. Although representatives of the genus are few in number and often poorly preserved, they are found throughout the Gunflint cherts.

The genus has been named *Eoastrion*—"dawn star"—to indicate the great antiquity and distinctive shape of its members. Two species have been established, one to accommodate the fossils with nonbranched filaments and the other the fossils with branched filaments. There are no clear analogies between the fossils and modern organisms, although in some respects *Eoastrion* resembles the curious iron- and manganese-oxidizing organism *Metallogenium personatum*.

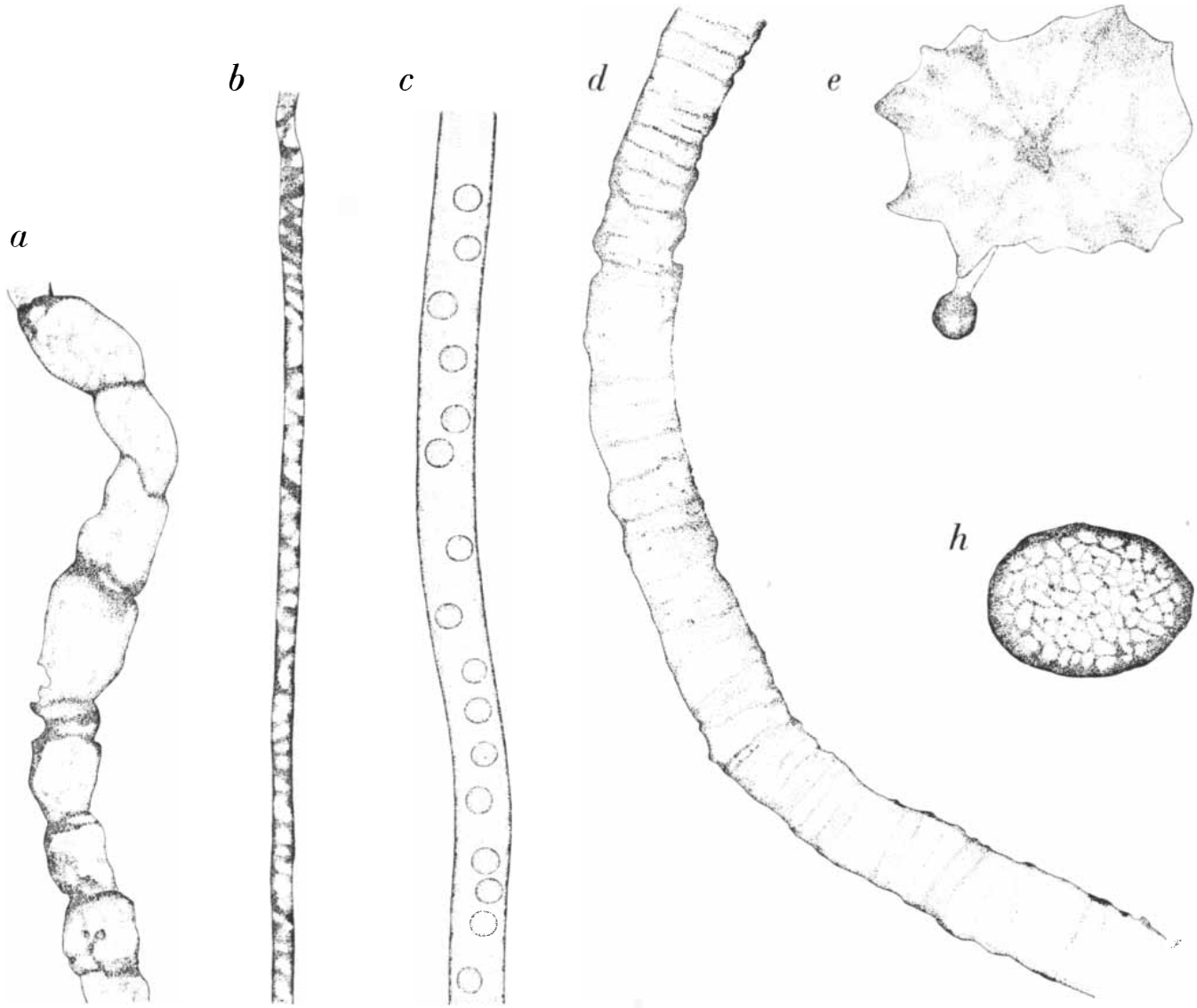
A most peculiar organism comprises the next of these genera. Its fossils are abundant in the cherts exposed near Kakabeka Falls, some 20 miles west of Thunder Bay. It consists of a bulb with a narrow stalk, surmounted by a structure that in some cases resembles an umbrella. The relative size of the three parts varies widely from specimen to specimen; the size of the bulb and the stalk together or of the umbrella alone ranges between 10 and 30 microns.

This odd plant has been assigned to the new genus *Kakabekia* and the species *umbellata* (which refers to the umbrella). Living organisms that superficially resemble it in form are certain multicellular polyps. All modern polyps, however, are many times larger.



FOSSIL BACTERIA found in the Gunflint cherts are enlarged 30,000 diameters in this electron micrograph. Some two billion years old, they look like living rod-shaped species.

The story of *Kakabekia* has had some interesting and continuing overtones. Late in 1964, quite independently (in fact, unaware) of paleontological investigations of the Gunflint fossils, Sanford M. Siegel discovered a strange new form while he was studying soil microorganisms that can survive extreme atmospheric conditions. The organism defied identification or assignment to any known taxonomic category. Siegel set it aside as being an enigma, although he kept his preparations, drawings and photomicrographs. A few months later a description of *Kakabekia* was published, and Siegel immediately noted a striking resemblance between his soil organism

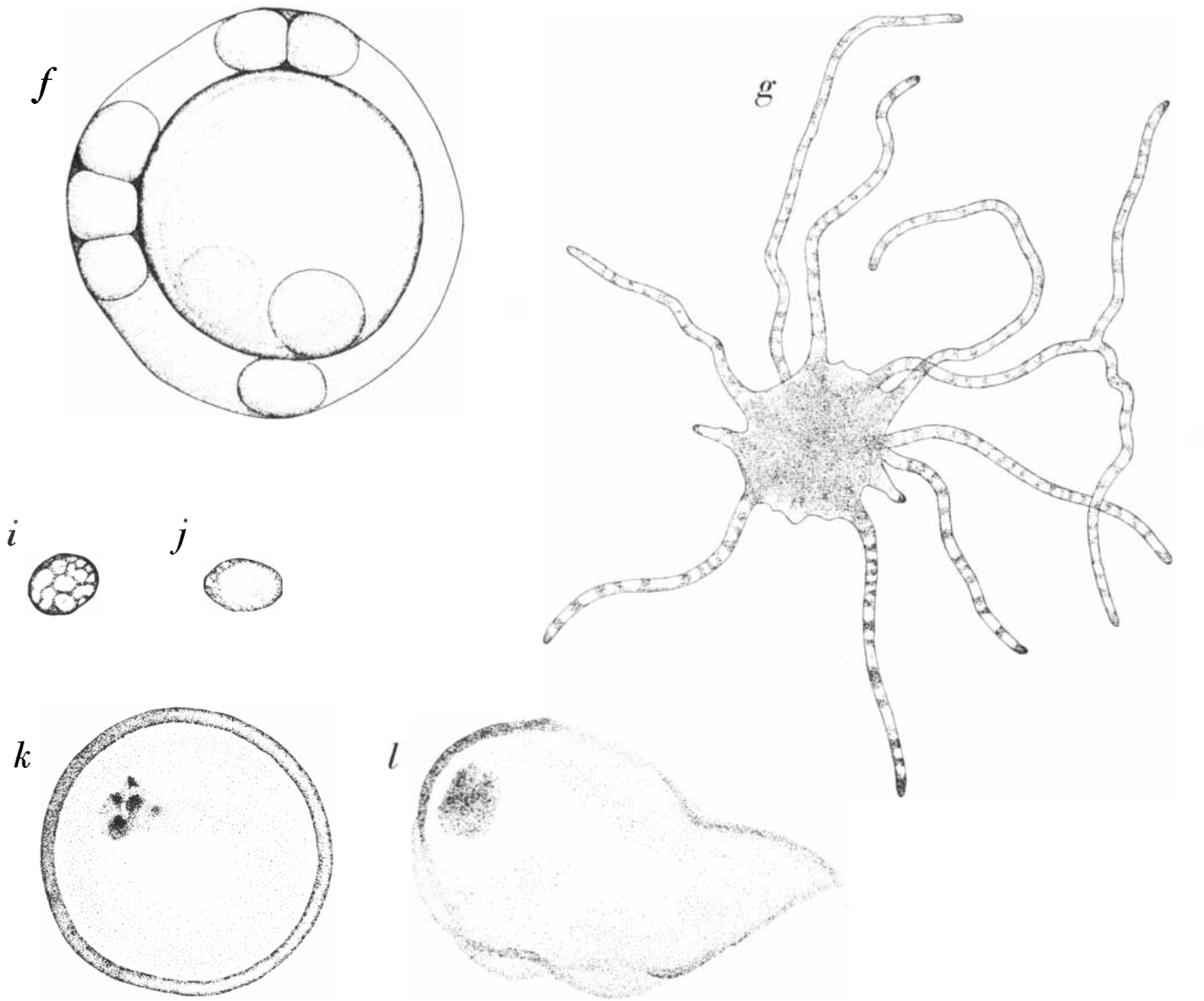


DIVERSITY OF FORM, evident among the plants fossilized in the Gunflint cherts, is indicative of evolutionary progress during the billion years that separate Fig Tree from Gunflint times. These composite drawings are based on a study of several specimens of each species and include three of the most unusual ones found. All are shown at the same scale: 2,500 times actual size. Filamentous organisms include two of the genus *Gunflintia: G. grandis* (*a*) and *G. minuta* (*b*). The other two are *Entosphaeroides amplus* (*c*) and *Animikiea septata* (*d*). The hydra-like *Kakabekia umbellata* (*e*) has a modern counterpart, if not a descendant, in a newfound soil

and some of the Gunflint specimens. Siegel's organism is very slow-growing, contains no chlorophyll and apparently has no nucleus; it may therefore be representative of a new group of prokaryotic microorganisms. It was first found in ammonia-rich soil collected at Harlech Castle in Wales, and it has since been recognized in soils from Alaska and Iceland and recently in soil from the slopes of the volcano Haleakala in Hawaii. Whether or not it is related to the two-billion-year-old *Kakabekia* is questionable, but the existence of two such bizarre forms is at least a remarkable evolutionary coincidence.

The eighth genus of Gunflint organisms comes from a single area near the easternmost outcropping of the chert, in the vicinity of Schreiber Beach. The organism consists of two concentric spheres; its outside diameter ranges from 28 to 32 microns. In most of the fossils the inner sphere is kept from contact with the outer one by as many as a dozen "spacers" in the form of small flattened spheroids. I have assigned this distinctive organism to the new genus *Eosphaera* ("dawn sphere") and the species *tyleri* (in honor of Tyler). No analogous living organism is known, nor has an organism resembling *Eosphaera* been found in any other Precambrian rocks. *Eosphaera* may be somewhat fancifully regarded as a "mistake" in evolution that did not survive the middle Precambrian.

Anyone who wanted to question that the organisms preserved in the Fig Tree cherts three billion years ago were photosynthetic could defend the negative position quite eloquently. Where the billion-years-younger Gunflint organisms are concerned, however, the affirmative evidence seems overwhelming. For one thing, the chemical analysis of organic material from the Gunflint cherts in several laboratories reveals the presence of the hydrocarbons pristane and phytane: two "chemical fossils" that can most reasonably be regarded as being breakdown products of chlorophyll. A second datum is the striking resemblance between the filamentous fossils that are the most abundant Gunflint forms and modern



organism. The globular *Eosphaera tyleri* (*f*) evidently failed to survive Precambrian times. *Eoastrion bifurcatum* (*g*), with its array of filaments, is one of two such species. Three spherical organisms that differ chiefly in surface markings are assigned to the single genus *Huroniospora;* they are *H. microreticulata* (*h*), *H. macroreticulata* (*i*) and *H. psilata* (*j*). A one-celled organism that has not yet been classified (*k and l*) has internal features suggestive of a nucleus; the second specimen may have been fossilized as the process of cell division began. If these are eukaryotic cells, a key evolutionary event took place far earlier than is now thought.

photosynthetic blue-green algae. A third is the small domes and pillars in the Gunflint chert that resemble the structures formed in shallow water today by dome-building photosynthetic algae.

One may add the evidence of the relative abundance in Gunflint organic matter of the two nonradioactive carbon isotopes carbon 12 and carbon 13. The carbon in the carbon dioxide of the earth's atmosphere normally consists of about 99 percent carbon 12 and 1 percent carbon 13. In the process of photosynthesis, however, plants tend to fix slightly more carbon 12 than carbon 13, so that plant tissues are even poorer in the heavier isotope. Measurements of the ratio of the two isotopes in Gunflint organic material were made by Thomas C. Hoering of the Geophysical Laboratory of the Carnegie Institution of Washington. The results indicate that the Gunflint material too is poor in carbon 13, and to a degree that is almost identical with the depletion in modern algae and other photosynthetic plants. The billion-years-older Fig Tree organic material shows a carbon-12-to-carbon-13 ratio that is about the same as the ratio in the Gunflint material. This result lends credence to the view that the alga-like Fig Tree organisms probably were photosynthetic too.

It seems reasonable to conclude that even if oxygen was only a trivial component of the environment in Fig Tree times, the Gunflint organisms represent the intermediate agency that brought about the oxygen-rich environment at the end of the Precambrian. This is a development of major importance. It is not, however, the only development or even the most important development of Gunflint times. The variety of form (and therefore presumably of function) represented by the eight genera of Gunflint plants demonstrates that terrestrial life had crossed the second evolutionary threshold—the threshold of diversification—no less than two billion years ago.

The crossing of the third threshold is clearly documented in a series of late Precambrian formations, consisting primarily of limestones, sandstones and do-

lomites, found along the northern rim of the Amadeus basin in the Northern Territory of Australia. One member of the series is the Bitter Springs formation; a ridge in the Ross River area, about 40 miles from Alice Springs, consists of strata from its lower and middle levels. The exposed formations include isolated beds of dense black chert and laminated rocks that are associated with fossil structures built by colonial algae.

No absolute age is known for the Bitter Springs formation. Its top strata, however, lie some 4,000 feet below the lowest of the rocks that in the Ross River area are the boundary between formations of Precambrian age and those of the succeeding Cambrian period. The generally accepted date for the beginning of the Cambrian period is 600 million years ago, so that the lower position of the Bitter Springs cherts makes them considerably older. The Bitter Springs formation also underlies Precambrian sediments that are known to be some 820 million years old on the basis of their rubidium-strontium ratio. I think it is reasonable to assume that the Bitter Springs cherts are roughly a billion years old. This makes them only half as old as the Gunflint cherts and less than a third as old as the Fig Tree cherts. I collected samples of the Bitter Springs cherts in the Ross River area in April, 1965, and I added them to the Fig Tree samples for study with Schopf that summer.

A preliminary analysis of the abundant microfossils in the Bitter Springs cherts indicates that at least four general groups of lower plants lived in the shallow seas or embayments that covered this part of central Australia in late Precambrian times. As one would anticipate, the plants included filamentous blue-green algae akin to such living forms as *Oscillatoria* and *Nostoc*. Some of these filaments are more than 75 microns long; they are thickest (about 1.4 microns) at the center and taper toward the ends to less than one micron.

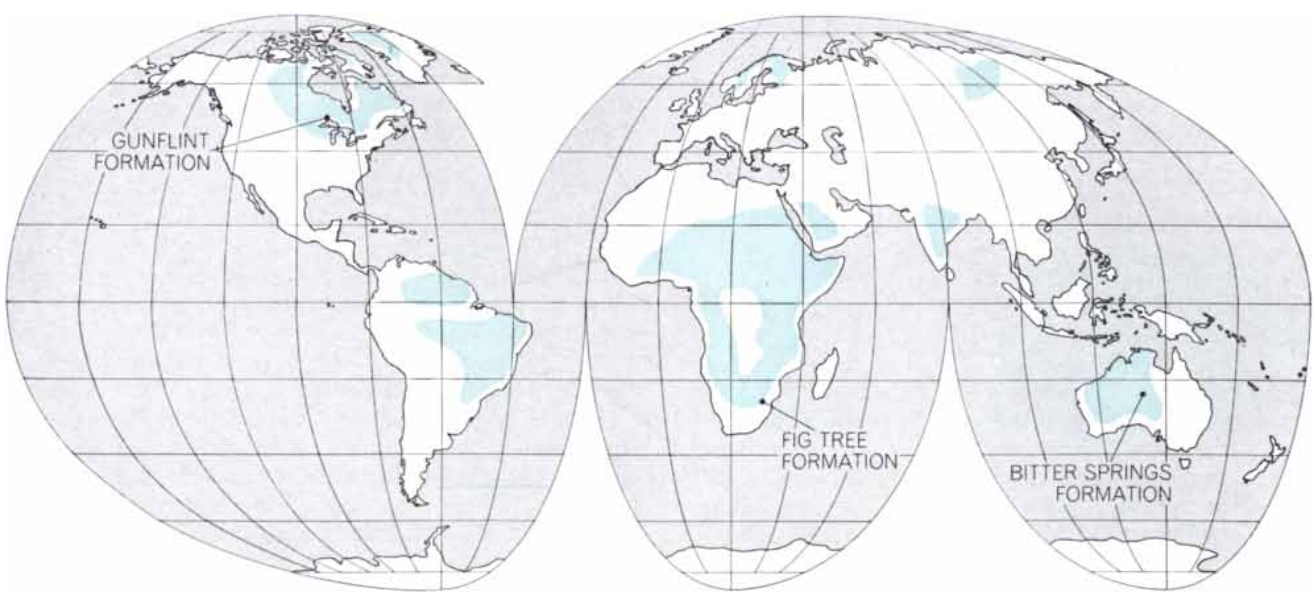
Our most exciting identifications during the preliminary analysis concerned the other three groups. On the basis of the internal structures that have been preserved, all three appear to represent various green algae. The green algae, unlike the blue-green algae, are eukaryotic! Thus the Bitter Springs cherts apparently contain the earliest-known fossil evidence that an organism potentially capable of sexual reproduction, or at least possessing a nucleus, had finally evolved.

By the time Schopf had finished his detailed analysis of the Bitter Springs specimens in 1968, he had concluded that they represent a total of three bacterium-like species, some 20 certain or probable representatives of blue-green algae, two certain genera of green algae, two possible species of fungi and two problematical forms. For one of the green algae, *Glenobotrydion aenigmatis*, an unusual coincidence of fossilization has preserved several specimens at various stages of mitotic division. By arranging the specimens in order one can recreate almost the entire sequence [*see illustration on page 42*].

With the discovery of a late Precambrian population of eukaryotic plants we approach the end of our story. The unequivocal appearance of the eukaryotic level of cellular organization at this point in earth history provides a welcome explanation for one of the principal puzzles of terrestrial evolution: Why do so many groups of higher organisms not appear in the fossil record until the span of geologic time is seven-eighths past? It is a good question, particularly in the light of what we know about the multicellular animals and higher algae early in the Paleozoic era.

Until recently the commonest explanation of the rarity of advanced organisms, multicellular animals in particular, before Cambrian times was that the supply of free oxygen in both the atmosphere and the hydrosphere had up to that point been extremely limited. Time was required to let the first prokaryotic organisms adjust to existence in an environment that had begun to contain this highly reactive element. Time was also needed for enough oxygen to leave the hydrosphere (where it was being produced by algal photosynthesis) and enter the atmosphere to establish a protective shield of ozone (O_3) between the earth's surface and the sun's harsh ultraviolet radiation. Until this shield existed neither shallow water nor bare ground would have been habitable.

An oxygen-poor environment was certainly a major obstacle in the path of

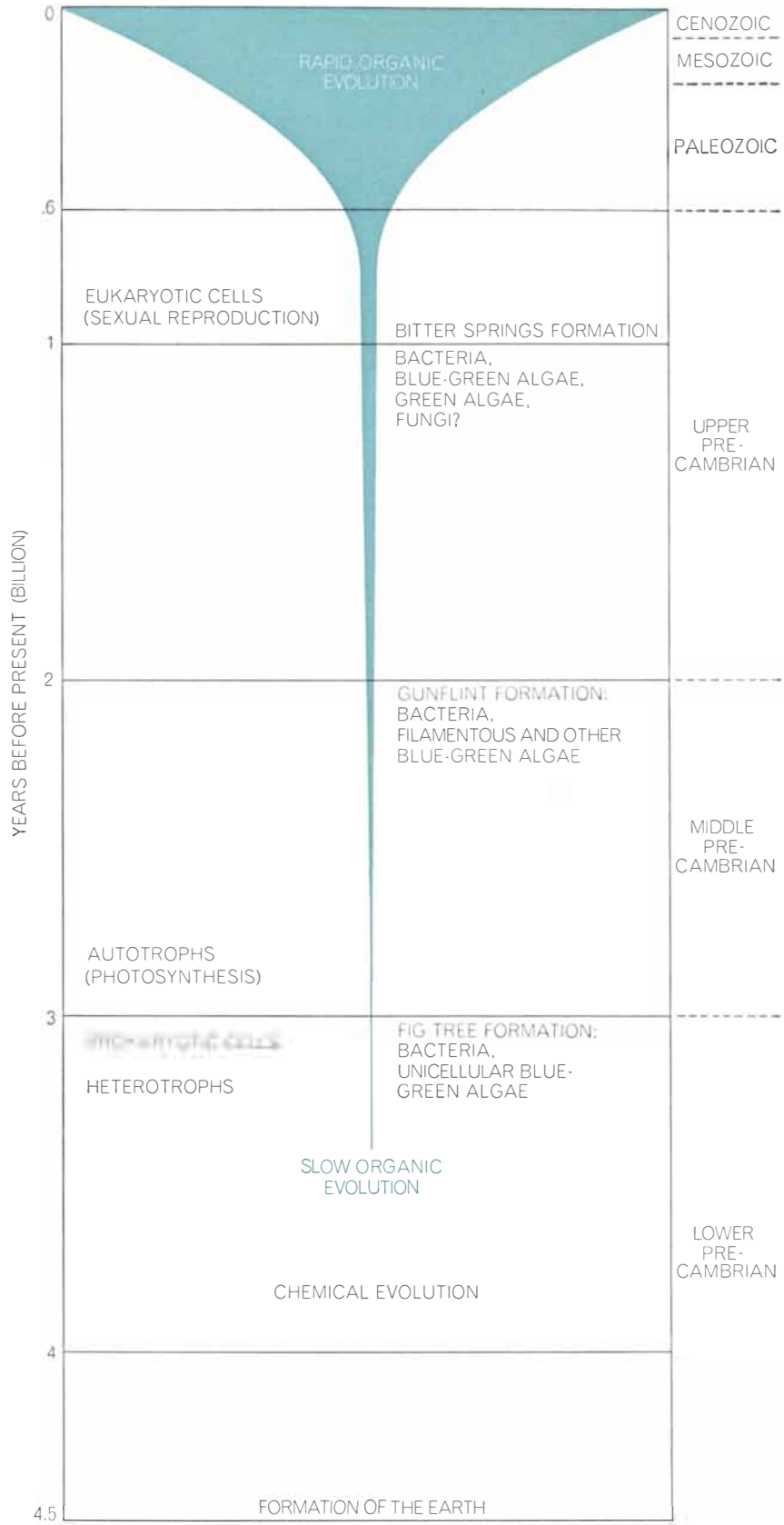


PRECAMBRIAN ROCKS occupy the old, low-lying "core" areas of continents throughout the world. Many, formed from accumulated sediments, are so altered by heat and pressure that any fossils have been obliterated. Some relatively unaltered exposures of Precambrian sediments, however, are rich in organic remains. Three such fossil-bearing Precambrian formations are shown on this map.

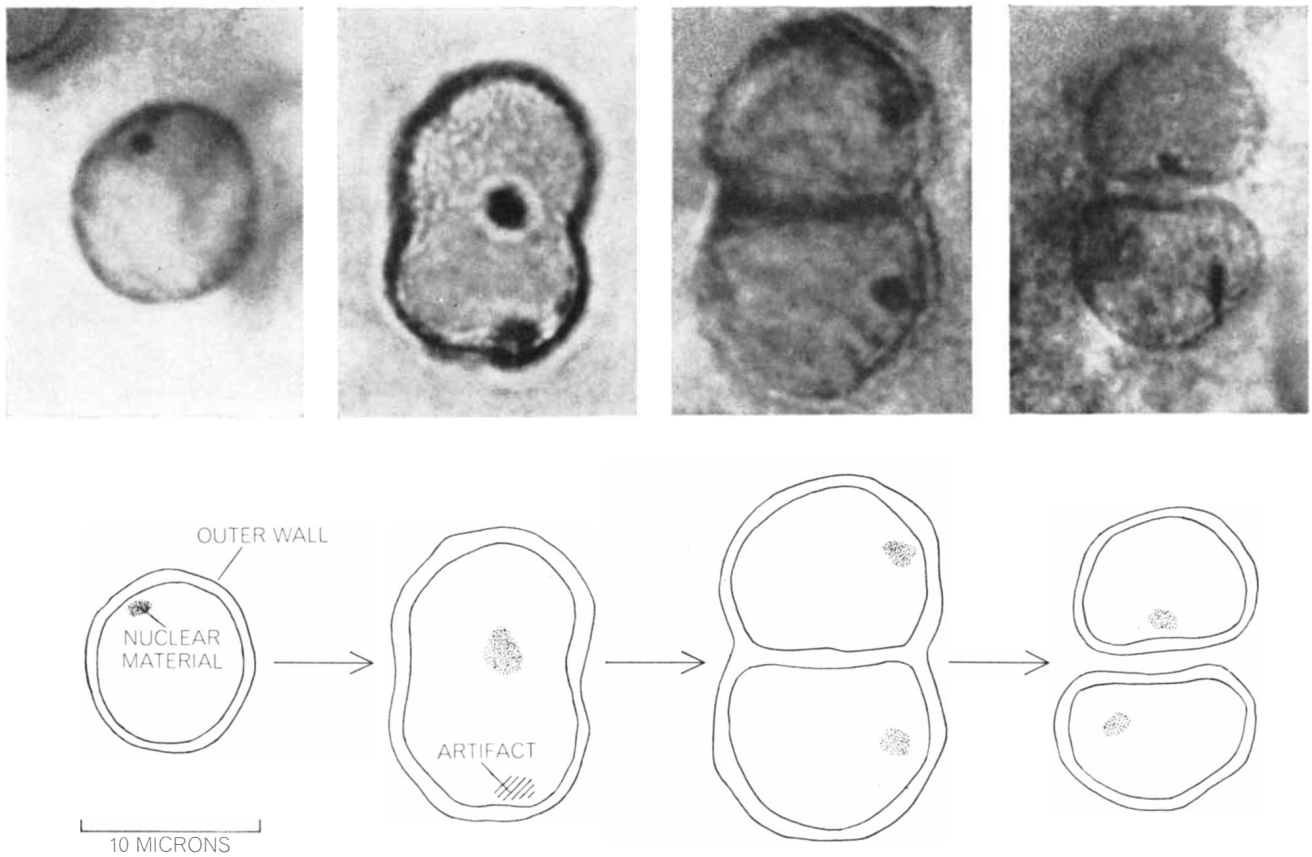
oxygen-dependent heterotrophs. In addition to the evidence provided by oxidized Precambrian formations, however, a number of recent studies indicate that the earth's atmosphere had actually accumulated enough oxygen to establish some kind of ozone shield considerably before the end of the Precambrian. The appearance of eukaryotic organisms late in the Precambrian, as indicated by the green algae of the Bitter Springs formation, provides a better explanation for the failure of higher organisms to appear until an even later time. The fundamental key to evolutionary progress is genetic variability. Sexual reproduction, which involves the recombination of heritable characteristics, is the highway to genetic variability and all its consequences, including the increased complexity of form and function at all levels of organization, that are thereafter apparent in the course of evolution.

This last of three thresholds, which separates the primitive world of cells without a nucleus from a world where sexual reproduction is possible, must have been crossed a long time before the formation of the Bitter Springs cherts. Only half a billion years or so later the Paleozoic seas were swarming with highly differentiated aquatic plants and animals, evolved from primitive forebears that had managed to cross all three Precambrian thresholds. Half a billion years does not seem to be evolutionary "room" enough to account for such epic progress. Moreover, there is evidence to suggest that developments in this direction may have begun in Gunflint times.

The Fig Tree, Gunflint and Bitter Springs cherts are not the only sources of Precambrian fossils, nor have Tyler, Schopf and I been the only investigators of the Precambrian fossil record. Indeed, work in the field has gone on for nearly a century. The emphasis has changed in recent years from an earlier concern with the curious "boundary" that has been traditionally accepted as separating the Precambrian from the beginning of the Paleozoic. We and our colleagues in many countries are primarily interested today in evidence that we hope will reveal even finer details of fossil cellular organization. It is a field that requires all levels of observation, from the macroscopic down to the electron microscopic. Workers in the field agree that the search for other stages and thresholds in the evolution of life must be focused on fine structures wherever these have been fortuitously preserved. The Precambrian fossil record is still meager, but significant gaps in the record are steadily



ORGANIC EVOLUTION is presented in terms of successively briefer episodes of biological advance. The Precambrian interval, the earliest and by far the longest, began when the earth was formed 4.5 billion years ago and ended 600 million years ago with the beginning of the Paleozoic era. The increasing abundance of species with the passage of time is indicated in color. Once organisms with eukaryotic, or truly nucleated, cells evolved, hastening evolutionary progress in late Precambrian times, the number of species multiplied explosively.



CELL DIVISION of a eukaryotic organism, a green alga of the genus *Glenobotrydion*, appears in the billion-year-old cherts of the Bitter Springs formation of Australia. J. William Schopf reconstructed the event (*drawings*), working with fossils that preserved individual organisms at different stages of division (*micrographs*). Existence of such biologically advanced algae in Bitter Springs times is proof that the evolutionary threshold leading to sexual reproduction and genetic variability had been crossed even earlier.

being filled. Indeed, the traditional concept of a clearly delimited Precambrian boundary may soon disappear from reconstructions of the history of terrestrial life.

Two final comments may be of interest to those who, like myself, are stimulated by the search for first causes no matter how often the search goes unrewarded. Some biologists now suggest that the organelles characteristic of the eukaryotic cell may once have been independent organisms that somehow came to live symbiotically inside larger host cells. It is not clear whether or not one of the host cell's responses to the presence of such a guest was a regrouping into a nucleus of the genetic material formerly scattered throughout the host's cytoplasm. If symbiosis was indeed the first step toward evolution of the eukaryotic cell, it may be that certain of the Gunflint organisms currently being studied show initial steps in this direction [*see middle illustration at right on page 36*]. A fascinating account of this transformation of various bacterial and algal organisms into components of the eukaryotic cell is given by Lynn Margulis of Boston University in a recent book. Mrs. Margulis' argument rests on biological grounds; the increasingly detailed Precambrian fossil record supports her thesis.

Astronomers and physicists have found evidence in recent years that molecules such as the hydroxyl radical (OH), carbon monoxide (CO), ammonia (NH_3), hydrogen cyanide (HCN) and formaldehyde (HCHO) are formed in the "empty" reaches of space. So far the ultimate in interstellar chemical complexity is represented by organic material that some investigators maintain they find in a peculiar class of meteorites known as carbonaceous chondrites. Until recently no carbonaceous chondrite had been recovered under circumstances that completely ruled out the possibility of accidental contamination by terrestrial organic material. As a result nagging questions about the chondrites have remained, particularly with regard to such biologically important molecules as amino acids (which are a *sine qua non* of terrestrial life). Recently, however, using stringent laboratory procedures to analyze carefully documented samples of the Murchison chondrite (which fell in southern Australia in September, 1969), Ponnamperuma and his associates at the Ames Research Center (in collaboration with Carleton B. Moore of Arizona State University and Ian R. Kaplan of the University of California at Los Angeles) seem to have proved the existence of extraterrestrial amino acids. Not only is the quantity of amino acids in the Murchison meteorite surprisingly high but also certain of them are unknown in terrestrial organisms and hence cannot be contaminants from the soil.

This finding opens up a new world of chemical evolution: a world of random synthetic processes not on the earth but in space, including the extraterrestrial formation of bodies (of which the carbonaceous chondrites seem to be fragments) that are rich in organic materials. The finding brings us back to the discussion at the beginning of this article. The chemical evolution of organic matter, the prelude to biogenesis on the earth, seems to have occurred elsewhere in the solar system or outside it. For knowledge of the earliest stages of organic evolution the biologist and paleontologist must rely on the chemist and astrophysicist.

We want to be useful ...and even interesting

Kodak

Renovated facilities

London's Royal Institution, where mankind in the person of Michael Faraday first saw clearly the principles of electromagnetic induction, has given the name Eastman Laboratory to certain recently renovated facilities. It commemorates an American entrepreneur who had Lord Kelvin on his board of directors.

Organizing the wares

Adsorption indicators
Atomic absorption supplies
Biological stains
Buffers
Carbohydrates and related reagents
Chelatometric indicators
Chromatography substrates, eluants, and reagents (TLC and GLC)
Clinical chemistry reagents
Colorimetric reagents for metals
Electron microscopy reagents and supplies
Electrophoretic (acrylamide gel) reagents and supplies
Enzyme substrates
Fluorimetric indicators
Laser dyes and Q-switches
Liquid crystals
Nonaqueous titrants, indicators, standards, solvents
Organic functional group determination reagents
Organic synthesis tool-compounds for reaction steps
Organometallic compounds and ligands
*p*H indicators
Plant growth regulators
Polymer laboratory chemicals
Protein and polypeptide reagents
Redox indicators
Scintillation-counting tool-compounds
Spectral sensitizers
Spectrophotometric solvents and reflectance products
Vacuum pump oils and greases

. . . and, of course, many of those categories are subdivided.

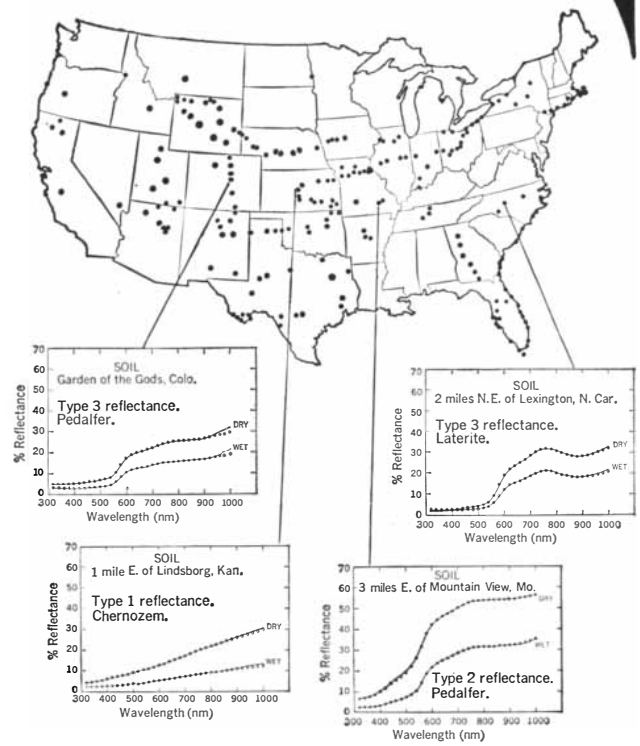
The new *Eastman Organic Chemicals Catalog 46* is quite a book. It's free, but we don't stress that fact. Anybody still in need of a copy for ordering chemicals should notify Dept. 412-L, Eastman Kodak Company, Rochester, N.Y. 14650.

Though orders keep us alive, take notice that orders for delivery to any address we suspect to be residential are subject to indefinite delay. This is a fail-safe policy in the interests of the public weal. We hope it will not cause too much inconvenience. Ambitious undergraduates will find the service agreeably prompt on institutional orders placed through a science faculty member.

The tome* offers minimal advice on use of the wares. It assumes you know what you are doing and are prepared to answer for the consequences, if any.

The value of such a huge list depends strongly on how good a job has been done in organizing it in various ways to anticipate wisely how the searcher will approach the search. No item appears in just one place in the book.

*1. We used 226 tons of paper for the job.
2. If all the copies were laid end-to-end on the long (11-inch) dimension, they would stretch for 21.3 miles.
3. If all the copies were stacked on top of one another, we'd have a pile 66 feet higher than the spires of the new World Trade Center in New York.



The colors of America

Both standardized wet and standardized dry, we have measured spectral reflectance of soils, sands, and silts predominant at each of 160 places in the U.S.A. We have then tried some taxonomy on the curves. They seem to fall into three types, one of which splits again.

Our work suggests that a spectrophotometer may not always be needed. Our study of the curves indicates that a good-to-excellent match of most of them can be calculated from reflectances measured at just five wavelengths. This can be done from aloft with readily available Kodak aerial film, narrow-band interference filters, and targets of known spectral reflectance. There are places where one click of the shutter provides more data than a thousand hand-collected samples like ours. The camera is mightier than the trowel.

Talk of collecting data from aloft has been leading to arguments. How far aloft? How much data. How much is it worth? Who decides? On what grounds?

While awaiting reasonable answers we felt that a study of the photographically accessible spectrophotometric variability of soil was something we ought to do, so H. R. Condit of the Kodak Research Laboratories did it.

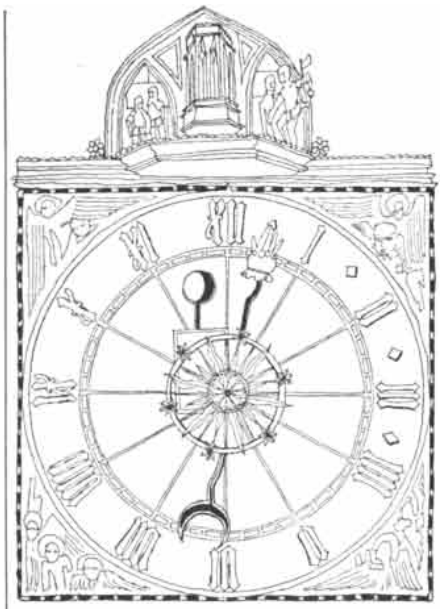
In Photogrammetric Engineering *for September, 1970 Condit gives a table of the constants which, when substituted in*

$$R_\lambda = a_{0,\lambda} + a_{1,\lambda}R_{440} + a_{2,\lambda}R_{540} + a_{3,\lambda}R_{640} + a_{4,\lambda}R_{740} + a_{5,\lambda}R_{860}$$

R_{440}=reflectance at 440nm, etc,

yields quite a decent fit to actual spectral reflectance, as seen from the dots along the above sample curves. The paper presents curves for 30 locations. Reprint on request from Eastman Kodak Company, Dept. 55W, Rochester, N.Y. 14650.

SCIENCE AND



Hard Times

Although U.S. academic institutions have been able to increase their spending for scientific research and education by an average of 8 percent per year in the past two years (1969 and 1970), the Federal Government accounted for only 2.4 percent of the increase both years. In 1970 about 40 percent of the total support for academic science was supplied by the Government. The difference between the 2.4 percent increase in Federal support and the average 8 percent increase in expenditures was made up by funds from a combination of sources: state governments, increases in student tuition and fees, foundation grants and private gifts. In terms of constant dollars the average increase of 8 percent per year in spending reduces to 5 percent. And when increases in college enrollments (13 percent in the two-year period) and operating costs are taken into account, the net effective support for academic science dropped at least 5 percent and more likely 10 percent between 1968 and 1970. These conclusions were reached by the National Science Foundation after it had sent questionnaires to 104 institutions granting doctoral degrees in science and had received replies from 662 science departments.

The hardest hit were large universities and private institutions, which were able to increase their science budgets by only 4 percent in the fiscal year 1970, compared with an average increase of 8.5 percent for all institutions and 10.9 percent for state universities. Overall the departments reporting the smallest increases in 1970 were physics and electrical engineering (1 percent), biological sciences and microbiology (4 percent) and biochemistry and sociology (6 percent). The departments with the largest increases were psychology (12 percent) and economics (16 percent). Nearly a third of the responding institutions said their life-science departments were most seriously hurt by the loss of Federal funds. Twenty-one percent said physics departments were most affected; 19 percent cited chemistry departments.

The number of teachers and postdoctoral fellows increased by only about 3.7 percent in 1970 as against 6.5 percent in 1969. The number of graduate students fell by somewhat less than 1 percent both years, except that the number supported by Federal funds dropped by 2.7 percent in 1969 and 5.1 percent in 1970. In the field of mathematics the number of graduate students supported by the Federal Government fell by 9.8 percent both years.

The American Way of Death (Cont.)

American men under 65 are twice as likely to die of heart attack as men living in Norway, Sweden or the Netherlands. Although American women of the same age are only about a third as prone to fatal heart attack as American men, even their rate is more than double that of Norwegian, Swedish and Dutch women. Each year about 175,000 Americans in the age group 35 to 64 die prematurely of coronary heart disease. A 14-year study in Framingham, Mass., has shown that a coronary attack often strikes without prior medical warning and that the majority of victims die within an hour of the event, two-thirds of them without ever reaching a hospital. A report on the Framingham experience by Tavia Gordon and William B. Kannel in *The Journal of the American Medical Association* concludes that improved medical care *after* a heart attack has occurred offers little hope for combating what the World Health Organization has described as potentially "the greatest epidemic mankind has faced."

In the Framingham study 102 men and 18 women died of coronary heart disease before their 65th year. For 58 percent of the men death was "sudden,"

THE CITIZEN

defined as occurring within an hour of the attack; among women somewhat fewer deaths (39 percent) were sudden. For both men and women sudden death was more likely if they were less than 55 years old at the time of the attack. "If we define an unexpected [coronary-heart-disease] death," the authors write, "as the death of a person without previous clinical evidence of *any* form of definite heart disease—a conservative definition, indeed—one half of all sudden CHD deaths were unexpected.... The progression from nil or inapparent disease to death appears to be very swift."

The authors acknowledge that although programs and techniques for preventing coronary heart disease are controversial, "a great deal is known about what kind of people die prematurely [of coronary heart disease]." The Framingham study and many others have shown that the risk of a heart attack is increased by such factors as hypertension, excessive body weight, elevated cholesterol in the blood and cigarette smoking. Commenting on the Framingham victims who had exhibited no previous sign of heart disease, the authors report that except for one person whose smoking habits were unknown all were cigarette smokers. They conclude: "Epidemiological studies have marshaled impressive evidence that the development of [coronary heart disease] is controlled by the local habits and conditions of life. It seems highly plausible... that modifications of our present way of life could be specified today that would ...dramatically reduce the premature toll of this disease and lower overall mortality in persons before age 65."

Camelot Revisited

Three members of the American Anthropological Association have been asked to evaluate the ethical aspects of fieldwork and consultation, including assistance to counterinsurgency efforts, in support of U.S. objectives abroad. The same issue had arisen in the mid-1960's over "Project Camelot," a covert research effort in Latin America financed by the Department of Defense. This time the problem has two aspects. The Anthropological Association not only is questioning the right of its members to accept action-oriented Government em-

ployment but also is considering the propriety of public comments on the ethical issue by certain members.

The three members of the evaluative committee are Margaret Mead of the American Museum of Natural History, William H. Davenport of the University of California at Santa Cruz and David L. Olmstead of the University of California at Davis. The issue confronting the committee arose in March, 1970, shortly after a nine-member Ethics Committee of the Association, appointed to report on post-Camelot ethical problems, had invited the membership to supply details of "anonymous cases diagnostic of ethical conflict" that might allow the Committee "to extract or to document general principles for the formulation of an ethical code." In forwarding the request through the Association newsletter Eric R. Wolf of the University of Michigan, the Committee chairman, pointed out that his group could not "take sides in any dispute nor adjudicate a particular set of issues," and that the Committee was not interested in the "names of persons or specific localities involved."

Before the end of March, Wolf's request was met in bizarre fashion. Michael Moerman of the University of California at Los Angeles is an anthropologist who has spent 14 months in a Thailand village and who has done occasional consultation work for the Agency for International Development. Someone with access to Moerman's files surreptitiously copied at least six documents in them and gave the copies to representatives of the Student Mobilization Committee to End the War in Vietnam. The Student Mobilization leadership then forwarded a selection of the documents to Wolf and to two other members of the Ethics Committee, Joseph G. Jorgensen of the University of Michigan and Gerald D. Berreman of the University of California at Berkeley. The documents contained the names of Moerman and four other American anthropologists in contexts suggesting that they were involved in counterinsurgency research. Simultaneously the Student Mobilization Committee prepared excerpts of the material for appearance in a special issue of its journal *Student Mobilizer*, and set a date for a press conference in Washington to coincide with the publication of the special issue on April 2.

Wolf and Jorgensen wrote to the Student Mobilization group, acknowledging that they had received the copied documents. They went on to state their view that the material was contradictory "in spirit and in letter" to an Association resolution concerning clandestine research, and their intention as members of the Ethics Committee to put "these most serious matters" before the Association. Their statement reached the Student Mobilization Committee in time to form a part of the material that was made public at the April 2 press conference.

On April 3, at a Berkeley meeting of the Association for Asian Studies where copies of the special *Student Mobilizer* issues were distributed, Berreman issued his own statement condemning counterinsurgency research. The statement was not, however, aimed exclusively at the Moerman documents, nor did it mention the Association's Ethics Committee or Berreman's status as a committee member. In none of Wolf's or his colleagues' statements early in April were Moerman or the other four anthropologists named. Their discretion was rendered ineffective, however, by the wide circulation given the Student Mobilization Committee statements.

During the ensuing weeks the governing body of the Association, an eight-member Executive Board, reacted to a succession of complaints and rebuttals by preparing a statement (issued in June) that directed the Ethics Committee thereafter to "refrain from public statements in the name of the Committee and to make clear in individual statements that they do not speak for the Committee or the Association." The Board statement further declared that Wolf and Jorgensen, "in communicating on this matter [of the Moerman documents] outside the Ethics Committee, went beyond the mandate of the Executive Board." Wolf and Jorgensen then resigned from the Ethics Committee. Later they prepared an extensive account of the episode, titled "Anthropology on the Warpath in Thailand," that was published in *The New York Review* at about the time of the Association's annual November meeting.

By this time both parties to the dispute—those concerned that a repetition of the Camelot disaster would harm all U.S. anthropological work abroad and those disturbed by a public accusation against their colleagues—had one ground for agreement: dismay over the apparently detached attitude of the Executive Board. The Board had proposed, presumably to damp the controversy, to seek outside financial aid for a future conference on "the ethical problems of research in Thailand and their wider implications to anthropologists working in other parts of the world."

At the November annual meeting the Association membership rejected the Board's proposal and moved to establish

Some things are changing for the better.

Electromagnetic Smog: A new way to avoid it

In the age of Aquarius, the need for better communications is more than a poetic ideal. With more than 6,000,000 radio transmitters operating in the U. S. alone, there is a constant danger of clogging the airways.

Let's take the case of land mobile communications. The nearly 2000 radio channels set aside for this purpose form a vast party line network shared by police, fire and ambulance services as well as a variety of commercial users. The system works properly only if the individual operators conform to the terms of their license for broadcast frequency and transmitted power. And only if the law of averages prevails: no messages would get through if all tried to transmit at the same time.

Clearly, chance will not prevent a collapse of the system indefinitely; some form of management is needed. Yet the sheer size of the network precludes continuous monitoring of all channels by manual techniques. Fortunately, it can now be done completely automatically.

The new HP 8580A Automatic Spectrum Analyzer is an automatic radio controlled by a dedicated minicomputer. The computer tunes it to one channel after another, rapidly and repeatedly scanning all the frequency bands allocated to land mobile communications. At each frequency, it listens to the carrier signal (not the message proper) gathering information on the use of that channel: broadcast frequency, transmitted power, how often messages are transmitted and for how long. The computer records the data and reduces it to information — channel usage by time of day and year, average message length, unauthorized usage, etc.— that is useful in making system management decisions. Computer output is also directly suitable for further digital processing.

Although it operates without human intervention, the 8580A is easily tailored to a variety of spectrum management problems. The key is a modular software package that accepts simple one-line statements in human-oriented language. It then translates them into detailed operating instructions for the 8580A's programmable instruments, to achieve the desired measurements automatically.

When equipped with programmable signal sources, the 8580A can also serve as an automatic stimulus/response test station. In a typical example, it could be used on a television receiver production line to measure the response of color, brightness and sound circuits as the set is tuned through all VHF and UHF channels. Prices start at $70,000. Yours for the asking, a 20-page brochure which describes the system's hardware and software and suggests many applications.

A better way to measure photons from UV to IR

It's our guess that any scientist who has ever made optical power measurements will greet the new HP 8330A/8334A Radiant Flux Meter System with more and more enthusiasm as he finds out more about it. Because it measures total radiant power over the entire IR to UV spectrum, with a flat response that remains accurate regardless of the spectral composition of the source of radiation. Because it's calibrated to better than ±5% traceable to NBS, at all wavelengths and at any power level, and reads out directly in absolute radiometric units. And because it is the first to have an automatic zero and a built-in self-calibrator that maintain system accuracy with no more effort than pushing a button.

Underlying many of these improvements in the state of the art is a unique thin-film thermopile detector whose extremely low thermal mass gives it a 10 to 100 times faster overall response than conventional thermopiles. Manufactured by vacuum deposition on a thin but tough substrate that gives it body without mass, the HP thermopile is considerably more rugged than previous laboratory designs. But the thermopile derives its most important characteristic, flat response, from a thin layer of gold, the likes of which no jeweler would care to use. Vaporized and deposited on the thermopile's 64 series-connected thermocouples, this gold has such a combination of particle size and structure that it traps and absorbs all incident photons from less than 0.3

to beyond 10 microns. It therefore looks black, exactly the opposite of the jeweler's requirements. Since it remains chemically inert, it does not form surface oxides that would act as mirrors. The gold layer also assumes an abnormally high electrical resistivity, so high that it does not "short" the thermocouple junctions which it overlays. Certainly not a jeweler's gold but a great one for thermopiles.

Equally important in terms of performance, a built-in self-calibrator maintains the accuracy of the system, at the touch of a pushbutton. Incorporating a low-frequency oscillator that delivers a precise amount of power to the thermopile, the automatic calibrator adjusts the gain of the measurement system to match the response of the thermopile. Thus compensated for all changes in sensitivity due to temperature, overload, mechanical shock, aging or even change of detector, the instrument always measures radiant power accurately and directly.

At $1100 for a complete system, the price of the 8330A/8334A represents another quantum improvement in the state of the art that will certainly encourage its use in a variety of electro-optical analytical and process control applications. A descriptive brochure of the system awaits your request.

Cardiac Catheterization: A Better Way for Patient and Physician

Over 100,000 victims of both cardiac congenital defects and cardiovascular disease visit a catheterization laboratory each year, a necessary step on the road back to good health. For this is where the physician performs cardiac catheterization by inserting a small tube (catheter) into a peripheral blood vessel and pushing it into the heart. Measurements are made of blood pressure in the heart and other physiological factors which give the doctor information he needs for diagnosis and treatment.

A typical "cath" procedure takes about two hours, after which the physician spends two to three more hours examining the data. Complex calculations convert the raw measurements into useable information about the condition of heart and valves.

Now, data sampling, analysis and display can be done automatically during catheterization, with HP's new 5690A computerized system. So fast that the physician can verify each step of the procedure and decide whether additional measurements should be made — thus avoiding the possibility of incomplete or faulty data.

Developed in a joint effort with the Stanford University Medical Center, the new HP 5690A computerized system is a completely integrated hardware and software system, performing data acquisition and real-time cardiac analysis from on-line sampling of pressure waveforms and from patient information the physician enters on a keyboard. The computer calculates all the hemodynamic parameters most often required — displaying results immediately. Price is approximately $85,000.

Where the usage level doesn't justify the full interactive capabilities of a computer-based system, an alternative approach uses the HP Programmable Electronic Calculator to perform the calculations. Merely by inserting a small magnetic card into the instrument, the physician enters instructions for the complex calculations. Then all he has to do is enter on the keyboard the catheterization measurement data.

Once basic data is entered, calculation takes less than five minutes and the desired information — information like cardiac output, stroke volume, total peripheral resistance, pulmonary and systemic A-V differences, % shunt — appears on the calculator's visual display and printer while the patient is still in the cath lab.

Fully documented HP cardiology programs available to all calculator users help speed catheterization data analysis. Additional programs to meet special requirements are easily prepared and permanently stored on magnetic cards for instant reuse. Calculator prices start at $3950.

Write us of your interest in either system and we'll send you complete information.

For those involved in equipping hospitals with electronic instrumentation, HP has just published a catalog of its medical electronic systems. You may obtain a copy of it (or the other material mentioned in this ad) by writing Hewlett-Packard, 1503 Page Mill Road, Palo Alto, California; Europe: 1217 Meyrin-Geneva, Switzerland.

HEWLETT hp PACKARD

Measurement, Analysis, Computation

00104

an *ad hoc* committee of inquiry with the mission of assessing both Government-financed anthropological research on Thailand and the actions of Ethics Committee members. It is that committee to which Mead, Davenport and Olmstead have been named.

Eutrophication Reconsidered

An excess of phosphorus is widely regarded as being a major factor in eutrophication, or overfertilization, of natural bodies of water. Recent studies involving both freshwater ponds and coastal marine waters indicate that the limiting factor in the massive growth of algae that accompanies eutrophication is nitrogen rather than phosphorus. The results suggest that current moves to substitute nitrilotriacetic acid (NTA), a nitrogenous compound, for phosphates in detergents may intensify the problem it is intended to relieve.

Seven farm ponds in Pennsylvania were studied by Richard W. Terkeltoub of the Agricultural Research Service of the U.S. Department of Agriculture. He found that algae grew in some ponds with phosphorus concentrations of less than the 15 parts per billion that is thought to be critical for the support of algae and did not grow in other ponds with phosphorus concentrations of more than 15 parts per billion. The marine work, which was done by John H. Ryther and William M. Dunstan of the Woods Hole Oceanographic Institution and reported in *Science,* involved waters of the eastern seaboard of the U.S., with particular reference to the fate of pollution emanating from New York harbor. Ryther and Dunstan found that the coastal waters normally contained about twice as much phosphate as algae can use, whereas all known forms of available nitrogen were in short supply. "Coastal waters already receive the sewage of roughly half the population of the United States," they write. "To replace a portion of the phosphate in this sewage with a nitrogenous compound and to then discharge it into an environment in which eutrophication is nitrogen-limited may be simply adding fuel to the fire."

Bright Idea

A new type of image amplifier based on the use of laser-pumped organic-dye cells has been invented by three physicists at Stanford University. The device, which enhances the brightness of any image that passes through it, could be useful in almost any situation where an object would be damaged by bright illumination but where the light must be bright enough for the object to be seen or photographed; a typical example is the microscopic examination of living microorganisms. The operation of the new device is described by its inventors, Theodore W. Hänsch, Frank Varsanyi and Arthur L. Schawlow, in a recent issue of *Applied Physics Letters.*

The possibility of using the principle of laser amplification to transmit and intensify optical images had been suggested as early as 1958 by Schawlow and Charles H. Townes. Until the current work, however, various approaches to the problem have lacked either sufficient gain or resolution, or their field of view has been too narrow. The new system, which is characterized as a compact, wide-angle, high-gain, high-resolution image amplifier, consists essentially of two glass cells (called the illuminator cell and the amplifier cell) filled with a special organic-dye solution that can be excited by the intense light of a pulsed nitrogen-gas laser. Light emitted by the excited dye molecules in the first cell is used to illuminate the object; light reflected from or transmitted by the object in turn triggers the laser-excited dye molecules in the second cell to emit light in such a way as to produce an amplified image that is an exact, but brighter, image of the original object. Unlike other light-amplification schemes, this approach results in an enhanced image that retains the colors of the original.

Besides microscopy, the potential areas of application of the dye-laser image amplifier range from spectroscopy, holography and short-time photography to new systems for television, motion-picture projection and large-scale optical information processing.

Crime and Punishment

Does punishment deter crime? There is good reason to believe it does. The important question is rather: How much punishment is needed to deter crime effectively, or, more specifically, when does the punishment go beyond what is needed to deter the crime? According to Franklin E. Zimring of the University of Chicago Law School, the findings of studies in this area "make an impressive case for the reduction of the present scale of major criminal sanctions" in the U.S.

In a monograph titled "Perspectives on Deterrence" published by the Center for Studies of Crime and Delinquency of the National Institute of Mental Health, Zimring reviews information on deter-

rence in crime control. He points out how hard it is to judge the efficacy of deterrence on the basis of experience, and he lists three "classic errors." One is the "Aunt Jane's cold remedy" fallacy: Take the medicine and your cold will go away within two weeks, which is translated into the assumption that a reduction in offenses that follows a certain change in enforcement or punitive action can be attributed to the change. Another is the "tiger prevention" fallacy, named for the joke about the man who snaps his fingers and moans in order to keep tigers away from New York, and cites the fact that there are no wild tigers near the city as proof that his actions are effective; this is translated into the assumption that a high-penalty policy is what is preventing a crime wave. The third is the "warden's survey" fallacy: A warden interviews men on death row and reports that none of them were deterred from committing their crime by the death threat, forgetting that he is dealing with a sample of men who by definition were not deterred.

In spite of these difficulties some useful studies have been conducted, Zimring writes. They suggest that apprehension and conviction do tend to reduce future criminality. In one survey people who were acquitted or had charges against them dismissed had a 91 percent rearrest record, compared with a 60 percent record among those convicted and punished. There is no strong evidence, however, that recidivism increases with leniency of sentence and there is some evidence to the contrary. Zimring urges that experiments be conducted with different degrees of punishment, with controls for variables other than punishment, in order to determine the effectiveness of particular policies.

Total Intravenous Feeding

It is now possible to feed a patient exclusively by vein, administering enough calories, amino acids, vitamins and essential trace elements to achieve normal growth in infants and weight gain in adult patients. The necessary techniques have been developed at the University of Pennsylvania School of Medicine by a team headed by Stanley J. Dudrick and Jonathan E. Rhoads. Intravenous infusions of saline solutions have been utilized since the end of the 19th century, and amino acids have been infused since about 1940. For several reasons it was not possible, however, to give enough food by vein to achieve a positive nitrogen balance, that is, to allow the patient's body to synthesize

more tissue (anabolism) than it was breaking down to produce energy (catabolism). The limit on intravenous feeding was set by the amount of water a sick adult can handle per day, by the caloric density (the number of calories per gram) of carbohydrates and proteins and by the concentration (about that of a 5 or 10 percent solution of dextrose) that can be introduced into a peripheral vein without causing serious inflammation and clotting.

Over a period of several decades the Pennsylvania group experimented with the infusion of fats (to get higher caloric content), the use of diuretics (to promote the excretion of water) and delivery through the large inferior vena cava instead of a peripheral vein; each method had drawbacks. In an effort to achieve a higher concentration of nutrients, Dudrick and Rhoads and their colleagues then tried feeding beagle puppies with a 30 percent nutrient solution by continuous (24-hour) infusion through the superior vena cava, the vein that returns blood from the head to the heart. In 1965 they achieved normal growth in puppies for as long as eight months.

The technique was subsequently applied to human babies and adults, Dudrick and Rhoads report in *The Journal of the American Medical Association*. Solutions containing about 20 to 25 percent dextrose, 5 percent fibrin hydrolysates (amino acids from the protein fibrin) and 5 percent vitamins, minerals and other necessary nutrients are infused continuously through a subclavian or jugular vein into the superior vena cava. By now about 100 infants with serious stomach and intestinal disabilities have been treated successfully. More than 1,000 adults have been treated: seriously malnourished, debilitated patients; victims of grave injuries, including burns; patients with disease or surgical conditions requiring absolute rest of the gastrointestinal tract. Cancer patients undergoing radiation or drug therapy can be strengthened by total intravenous feeding, and the team hopes to find ways of selectively starving a tumor while feeding the patient. The technique is valuable in kidney and liver disease, in which precise control of nutrients is essential, and the ability to control diet precisely should also make it a research tool.

Like some other recently developed techniques, total intravenous feeding can present a major ethical problem since it can support life when normal body functions fail. Dudrick and Rhoads observe that "the aim of such support, however, should be to prolong life and not merely to prolong death."

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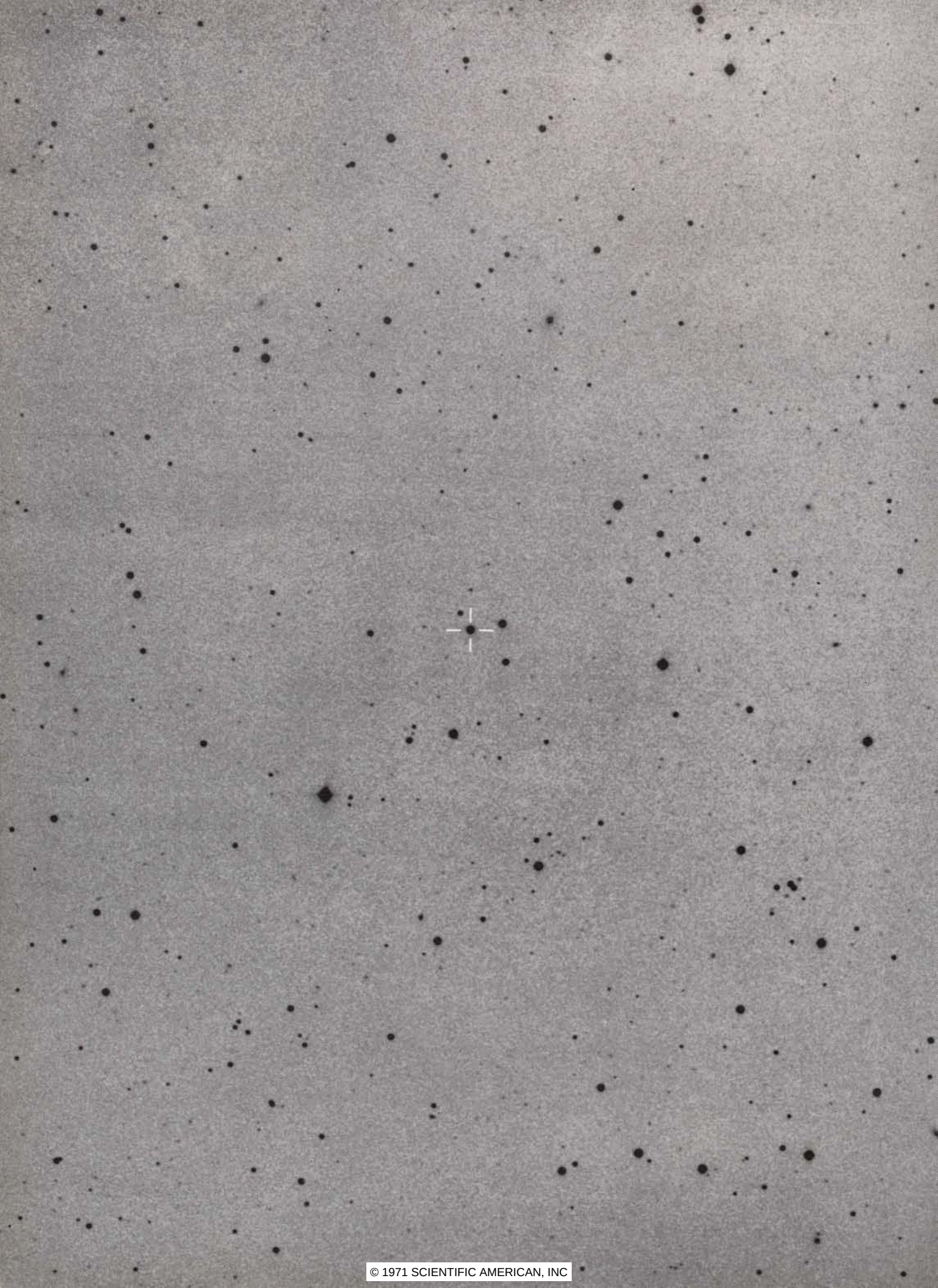


THE EVOLUTION OF QUASARS

It seems that they were much more plentiful when the universe was young than they are today. Their light takes so long to reach us that we can observe millions of them that have long been extinct

by Maarten Schmidt and Francis Bello

Since light has a finite velocity the astronomer can never hope to see the universe as it actually exists today. Far from being a handicap, however, the finite velocity of light enables him to peer back in time as far as his instruments and ingenuity can carry him. If he can correctly interpret the complex messages coded in electromagnetic radiation of various wavelengths, he may be able to piece together the evolution of the universe back virtually to the moment of creation. According to prevailing theory, that moment was some 10 billion years ago, when the total mass of the universe exploded out of a small volume, giving rise to the myriad of galaxies, radio galaxies and quasars (starlike objects more luminous than galaxies) whose existence has been slowly revealed during the past half-century.

Optical observations have shed little light on the evolution of ordinary galaxies because even with the most powerful optical telescopes such galaxies cannot be studied in detail if they are much farther away than one or two billion light-years. The astronomer sees them as they looked one or two billion years ago, when they were already perhaps eight or nine billion years old. Quasars, on the other hand, provide a direct glimpse of the universe as it existed eight or nine billion years ago, only one or two billion years after the "big bang" that presumably started it all.

Some 50 years ago the first large telescopes had shown that the light from distant galaxies is shifted toward the red end of the spectrum; the more distant the galaxy, the greater its red shift and the higher its velocity of recession. Like raisins in an expanding cosmic pudding, all the galaxies are receding from one another. From the observed velocities of recession one can compute that some 10 billion years ago all the matter in the universe was jammed into a tiny volume of space.

The term quasar, a contraction of "quasi-stellar radio source," was originally applied only to the starlike counterparts of certain strong radio sources whose optical spectra exhibit red shifts much larger than those of galaxies. Before long, however, a class of quasi-stellar objects was discovered with large red shifts that have little or no emission at radio wavelengths. "Quasar" is now commonly applied to starlike objects with large red shifts regardless of their radio emissivity.

BRIGHTEST QUASAR and first member of its class to be recognized is 3C 273, indicated by the reticle in the photograph on the opposite page. The negative print was made from a 1-by-1⅜-inch portion near the edge of a 14-inch square plate taken with the 48-inch Schmidt telescope on Palomar Mountain as part of the National Geographic Society–Palomar Sky Survey. In 1962 the starlike object was found to coincide with the position of a strong radio source designated No. 273 in the third catalogue compiled by radio astronomers at the University of Cambridge. The optical magnitude of 3C 273 is 13. In the entire sky there are at least a million stars of that magnitude. A study of 3C 273's strange spectrum revealed, however, that its light was shifted toward the red end of the spectrum by an amount that indicated the object was receding at about one-sixth the velocity of light. This implied that it was not a nearby star but an object between one billion and two billion light-years away. A galaxy at the same distance would appear at least four magnitudes fainter, which means that 3C 273 is intrinsically at least 40 times brighter. The term "quasi-stellar radio source," or quasar, was coined to describe 3C 273 and other starlike objects exhibiting a large red shift.

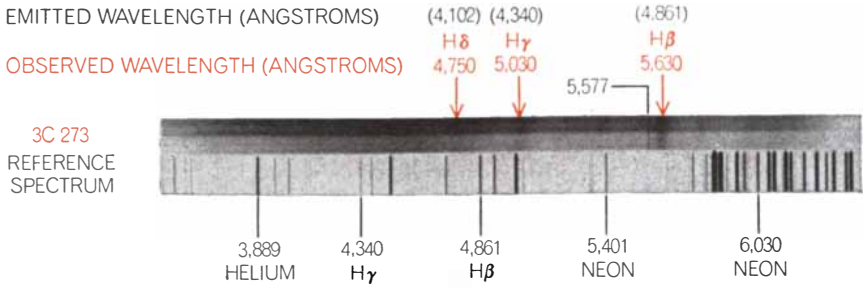
This article is based on the hypothesis that the quasar red shifts are cosmological, that is, they are a consequence of the expansion of the universe and thus directly related to the distance of the object. On that hypothesis quasars are very remote objects. According to a contrary hypothesis, which will be discussed toward the end of the article, quasars are relatively close objects.

A recent study of quasars carried out with the aid of the 200-inch Hale telescope on Palomar Mountain has provided evidence that these extremely luminous objects evolved quite rapidly when the universe was young. The study indicates that quasars were about 100 times more plentiful when the sun and the earth were formed some five billion years ago than they are today. They were perhaps more than 1,000 times more plentiful at a still earlier epoch, say eight or nine billion years ago. Earlier than that, however, there may have been fewer quasars, perhaps because conditions in the universe had not yet favored their development.

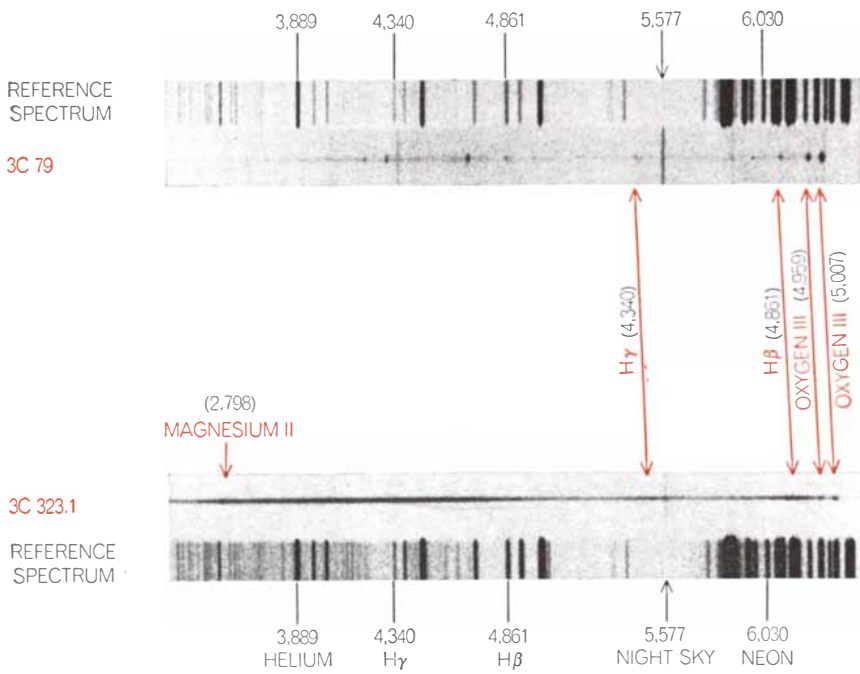
The study embraced all the quasars in two areas of the sky representing a thousandth of the total celestial sphere. By extrapolation one can say with reasonable confidence that a complete sky survey with the largest telescopes should reveal on the order of 15 million quasars. The overwhelming majority are so far away that they almost certainly burned themselves out in the billions of years required for their light to reach us. All of them, of course, can still be studied telescopically, given the time and the inclination. If, however, it were possible to conduct an instantaneous survey of the universe, one might find that only about 35,000 quasars are in existence and radiating with their characteristic intensity at the present time. These find-

ings are in conflict with the "steady state" hypothesis, which holds that the universe has always looked exactly the way it does today. That hypothesis postulates that new matter is continuously being created to maintain the expanding universe at a constant density.

After 10 years of intensive study by optical and radio astronomers quasars remain among the most puzzling of all celestial objects. Assuming that they are at cosmological distances, one can easily show that many quasars are from 50 to 100 times brighter than entire galaxies containing hundreds of billions of stars. Unlike the light output of normal galaxies, the light output of some quasars has been observed to change significantly in a matter of days. The only explanation is that some variable component of a quasar, if not the entire quasar, may be not much larger than the solar system.



PORTION OF SPECTRUM OF QUASAR 3C 273 shows three prominent emission lines centered at 4,750, 5,030 and 5,630 angstroms, corresponding to the hydrogen emission lines delta, gamma and beta in the Balmer series. The upper and lower halves of the spectrogram were given different exposures to facilitate study. The three emission lines are produced by hydrogen atoms in various states of excitation. Two of the three lines, H gamma and H beta, also appear in the reference spectrum at their normal emission wavelength: 4,340 and 4,861 angstroms. The normal wavelength for H delta is 4,102 angstroms. The red shift, *z*, is obtained by subtracting the normal wavelength from the observed wavelength and dividing the difference by the normal wavelength. For 3C 273 *z* is .158, indicating the quasar is receding at nearly a sixth the speed of light. The sharp line at 5,577 often appears in spectra of astronomical objects and serves as a convenient reference point; it is produced by excited oxygen atoms in the upper atmosphere. This spectrogram and others in this article were made by one of the authors (Schmidt), who provided the original interpretation of 3C 273's spectrum.



CONTRAST BETWEEN QUASAR AND RADIO GALAXY is shown by these two spectra. The spectrum at the top is that of the strong radio galaxy 3C 79, which has a red shift of .256. The bottom spectrum is that of quasar 3C 323.1, whose red shift is just slightly greater: .264. The radio galaxy produces a substantial number of sharp emission lines. Four of the lines in the right half of its spectrum are identified and compared with their much broadened counterparts as they appear in the spectrum of the quasar. Quasars characteristically emit strongly in the ultraviolet part of the spectrum. A common emitting ion is singly ionized magnesium, designated magnesium II, which has an emission wavelength of 2,798 angstroms.

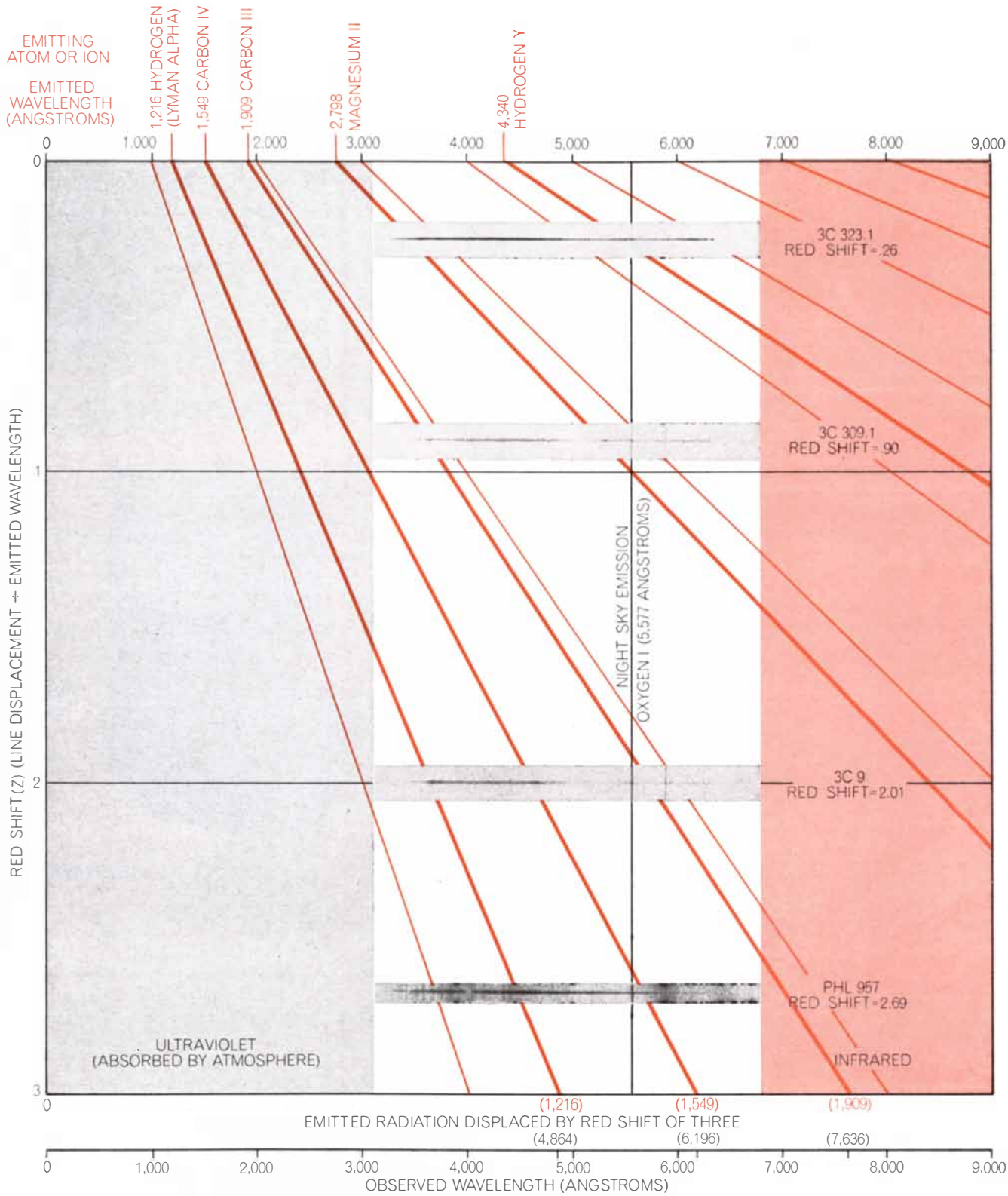
The Discovery of Quasars

Before 1960 radio astronomers had identified and catalogued hundreds of radio sources: invisible objects in the universe that emit radiation at radio frequencies. From time to time optical astronomers would succeed in identifying an object—usually a galaxy—whose position coincided with that of the radio source. Thereafter the object was called a radio galaxy. The large majority of radio sources remained unidentified, however, and the general belief was that the source of the emission was a galaxy too far away, or at least too faint, to be recorded on a photographic plate.

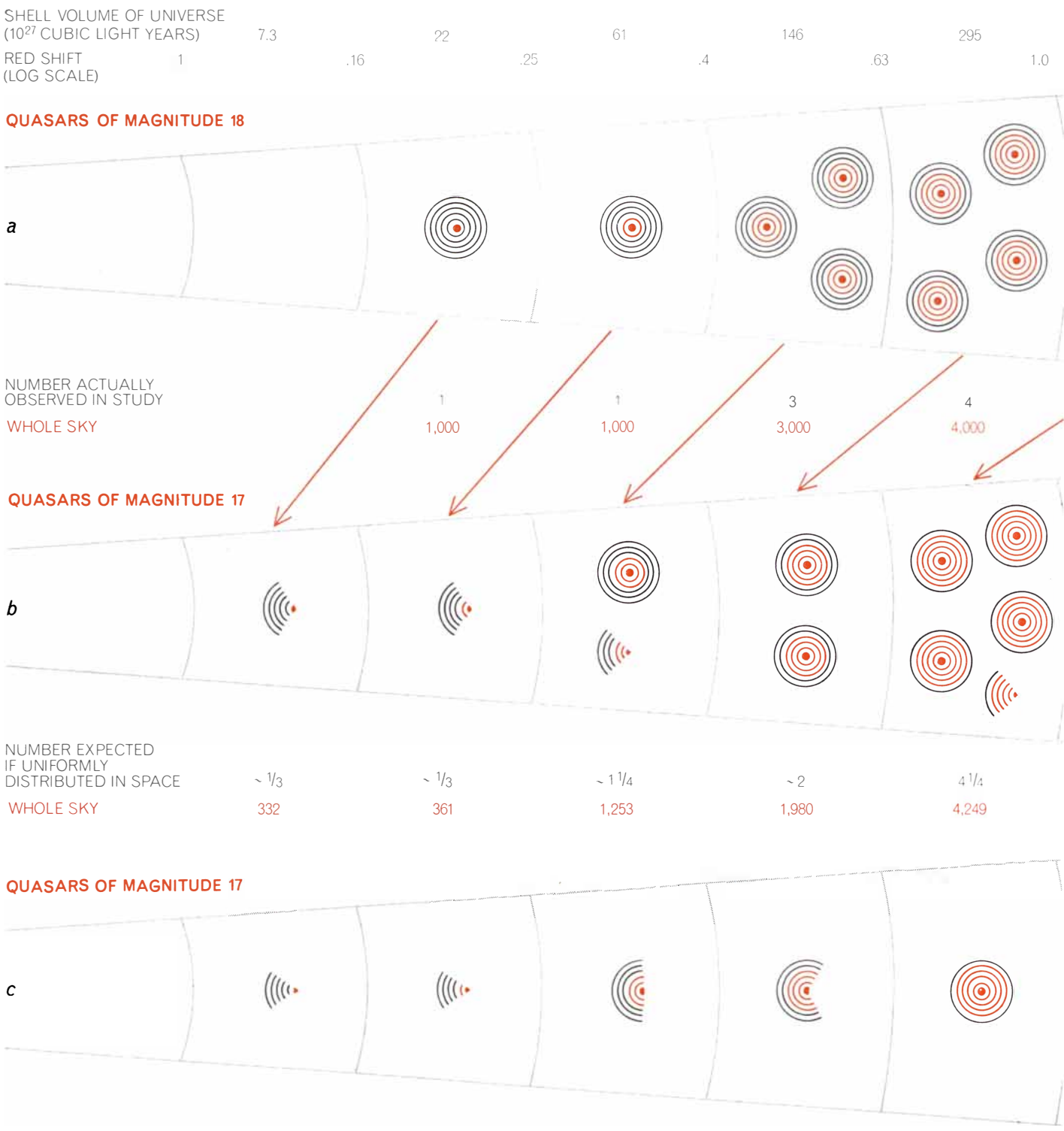
In 1960 Thomas Matthews and Allan Sandage first discovered a starlike object at the position given for a radio source in the Third Cambridge ("3C") Catalogue, compiled by Martin Ryle and his colleagues at the University of Cambridge. The radio object 3C 48 coincided in position with a 16th-magnitude star whose spectrum exhibited broad emission lines that could not be identified. Not only did the object emit much more ultraviolet radiation than an ordinary star of the same magnitude but also its brightness varied by more than 40 percent in a year.

Object 3C 48 was thought to be a unique kind of radio-emitting star in our own galaxy until 1963, when the strong radio source 3C 273 was identified with a starlike object of 13th magnitude and one of the authors (Schmidt) recognized that most of the puzzling lines in its spectrum could be explained as the Balmer series of hydrogen lines, shifted in wavelength toward the red by 15.8 percent, or .158 [*see illustration on page 54 and upper illustration at left*]. Red shifts are commonly expressed as a fraction or percentage obtained by dividing the measured displacement of a line by the wavelength of the undisplaced line. With this clue it was immediately evident that the lines in the spectrum of 3C 48 had a red shift of .367 [see "Quasi-stellar Radio Sources," by Jesse L. Greenstein; SCIENTIFIC AMERICAN, December, 1963].

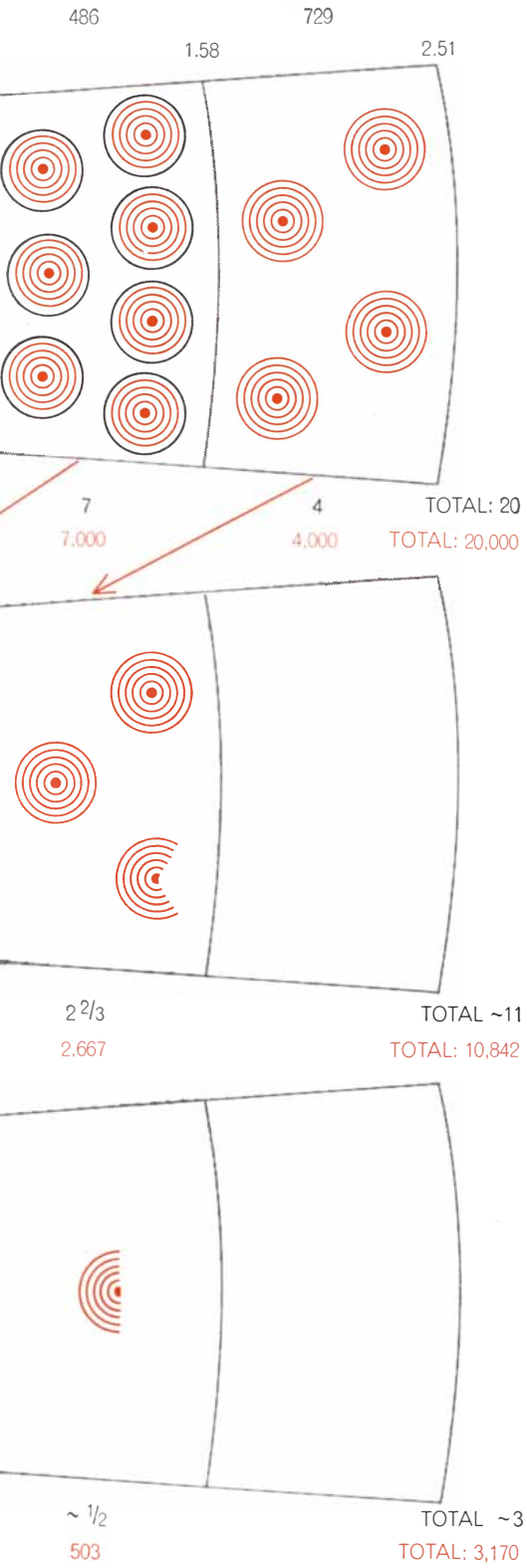
Such large red shifts, equivalent to a significant fraction of the velocity of



FOUR QUASAR SPECTRA are positioned on a diagram that shows how radiation emitted at one wavelength billions of years ago is "stretched" on its long journey through space by the presumed expansion of the universe. At least two emission lines are needed to establish the red shift of an astronomical object. A single line could represent any line shifted by any arbitrary amount. Here the heavy slanting lines correspond to the radiation emitted by hydrogen (Lyman alpha), carbon IV, carbon III, magnesium II and hydrogen (gamma). The roman numerals are one greater than the number of electrons missing from the atom. At a red shift, z, of 1 the Lyman-alpha line is observed at 2,432 angstroms; at a red shift of 2 the line is observed at 3,648 angstroms; at a red shift of 3 it would appear at 4,864 angstroms. Thus when z equals 2 the initial wavelength is stretched exactly three times; when z equals 3, four times and so on. The quantity $1 + z$ expresses how much the universe has expanded between the emission of a photon and its observation. Only two quasars are known with a red shift greater than 2.5; one of them is PHL 957, whose spectrum appears here. Its spectrum was made with an image-tube spectrograph; the other three spectra were recorded directly on photographic film. The photons that produced the spectrum of PHL 957 left the quasar when the universe was only about 13 percent of its present age.



NUMBER OF QUASARS has been estimated by identifying and determining the red shifts of all the quasars in sample fields representing one-thousandth of the whole sky. The sample consisted of 20 quasars with an optical, or apparent, magnitude of about 18. It was clear from their red shifts, however, that some are much farther away than others and therefore are intrinsically brighter, as depicted in *a*. The red-shift intervals have been chosen so that the quasars in any given "shell" of the universe are on the average one magnitude (2.5 times) brighter in absolute luminosity than those in the next shell inward. Thus the four quasars in the sample box representing the most remote shell (red shift: 1.58 to 2.51) are each 100 times more luminous than the single quasar in the box whose red shift is between .16 and .25. Now, if quasars are uniformly distributed in space, and if there are 4,000 of maximum luminosity in the most remote shell, one would expect to find a proportional number in the next shell inward, whose volume is only two-thirds that of the outer shell. Two-thirds times 4,000 is 2,667. Thus diagram *b* shows that in the red-shift interval between 1 and 1.58 one would expect to find 2,667 quasars of maximum luminosity in the whole sky (or, proportionately, 2⅔ quasars in the small area actually sampled). In photographs these 2,667 should appear one magnitude brighter (magnitude 17) than the 4,000 of the same intrinsic brightness that are farther away. Using the same assumptions, one can estimate the number of quasars in still nearer shells.



The total number is 10,842, distributed as shown in *b*. One concludes, therefore, that if quasars are uniformly distributed in space, one should observe about twice as many 18th-magnitude quasars as 17th-magnitude quasars. In actuality, however, surveys show that the number of quasars goes up by a factor of about six per magnitude. To satisfy this observation there can be only about 3,000 quasars of the 17th magnitude in the whole sky. An appropriate red-shift distribution for that approximate number is shown in *c*.

light, ruled out the possibility that 3C 273 and 3C 48 were stars in our galaxy. It was proposed that the red shifts are cosmological, which implies that the two objects have to be billions of light-years away and therefore extremely luminous to look as bright as they do in our night sky. They soon became known as quasars. Within the next few years quasars with even larger red shifts were discovered, including some with red shifts of more than 2, or more than six times the largest red shift ever observed for an ordinary galaxy. On the cosmological hypothesis, a red shift of 2 suggests that the light from the object has been traveling for about 80 percent of the age of the universe.

The Quiet Quasars

Several hundred radio sources have now been identified with starlike objects. Most of the identifications are made on the basis of positions provided by two or more radio telescopes spaced from several hundred meters to several thousand kilometers apart, used as an interferometer. The technique yields a precise measure of the difference in the time required for radio waves from the source to reach each telescope of the interferometer. One can then locate the source with an accuracy of between one second and 15 seconds of arc. Once the search has been narrowed to an optical candidate the final test is to see if its spectrum shows a red shift. More than half of the objects identified on the basis of their radio position usually turn out to be quasars. The spectroscopic test is unambiguous because the maximum red shift ever recorded for a star is .002; the smallest red shift for a quasar identified on the basis of its radio emission is .158 (for 3C 273).

It was noticed early that quasars usually emit rather strongly in the ultraviolet part of the spectrum. In 1964, when radio positions were known with considerably less accuracy than they are today, Ryle and Sandage conceived the idea of using ultraviolet strength as a clue in searching for optical counterparts of radio sources. They used a technique in which a single photographic plate of a star field was exposed to blue light and then was shifted slightly and exposed to ultraviolet radiation. By visual examination it was possible to readily distinguish strong ultraviolet emitters from normal stars.

In 1965 Sandage noted that objects with excess ultraviolet emission were much more plentiful than known radio sources in typical star fields. He soon discovered that some of these "blue stellar objects" exhibit red shifts that qualify them as quasars even though no radio emission has been detected from them. Most of the other strong ultraviolet emitters turn out to be white-dwarf stars in our own galaxy. Thus only a small fraction of quasars are strong radio emitters. The rest are radio quiet, or virtually so. It may be that a typical quasar is a strong radio emitter for only a small part of its life-span. Alternatively, it may be that relatively few quasars are born to be strong radio sources.

Two years ago Sandage and Willem J. Luyten published photometric analyses of 301 blue objects in seven survey fields. They counted quasar candidates tentatively selected from these blue objects and estimated that in one square degree of the sky (roughly equal to five times the area of the moon) there is, on the average, .4 quasar brighter than magnitude 18.1. They also estimated that there are five quasars per square degree brighter than magnitude 19.4, and that tentatively there are as many as 100 brighter than magnitude 21.4. Over the entire sky they estimated there may be 10 million quasars of the 22nd magnitude or brighter.

The greater the magnitude, of course, the dimmer the object; every increase of five magnitudes (say from the 18th magnitude to the 23rd) corresponds to a decrease by a factor of 100 in brightness. The number of quasars increases steeply with magnitude, by a factor of about six per magnitude. This steep increase is incompatible with a uniform distribution of quasars in space, as we shall see.

Counting Verified Quasars

The objects isolated by Sandage and Luyten are defined as "faint blue objects [with] an ultraviolet excess." For a detailed statistical study one has to obtain the spectrum of each "faint blue" candidate individually to establish whether or not it is really a quasar. One of the authors (Schmidt) began this task about four years ago, working with several of the star fields examined by Sandage and Luyten. The ultimate goal of the study is to establish how quasars are distributed by red shift (distance) and luminosity.

Of 55 faint blue objects investigated in two of the Sandage-Luyten fields, 32 turned out to have negligible red shifts and therefore could be rejected as being dwarf stars within our own galaxy. The 23 remaining objects exhibited spectra characteristic of quasars, and all but one

of the spectra contained the minimum of two lines needed for establishing a red shift. A single line could represent almost any emitting atom red-shifted by any arbitrary amount. When a spectrum contains two lines, however, it is almost always possible to assign a unique red-shift value that identifies a reasonable emission wavelength for each line [*see illustration on page 57*]. Unfortunately the spectra of some quasars show only a single clear line, thereby frustrating efforts to establish their red shift. Although the red shifts assigned to several of the objects are still tentative, the overall distribution must be essentially correct. The red shifts range from .18 to 2.21. None of the 23 quasars appears in any of the catalogues of strong radio sources.

At this stage it will be most useful in our discussion to concentrate on the quasars of 18th magnitude in the sample. There are 20 such quasars. Since the 20 objects exhibit a variety of red shifts, however, we know they must lie at vastly different distances and therefore must differ greatly in *absolute* luminosity even though they look equally bright to an observer.

To express these differences in absolute luminosity one can classify the objects by red shift in such a way that each red-shift category represents a step of one magnitude in absolute luminosity. The relation between the red shift and the magnitude of a standard source depends on the properties of the universe. In the cosmological model followed in this study a quasar of 18th magnitude whose red shift falls in the range between .25 and .4 is intrinsically brighter by one magnitude than a nearer object whose red shift lies between .16 and .25. Six red-shift categories, each corresponding to a step of one magnitude in absolute luminosity, are enough to cover the range of red shifts actually exhibited by the 20 objects. The brightest members of the group are five magnitudes, or 100 times, brighter than the least luminous.

When the 20 quasars were grouped by red shift in this way, their distribution was found to be similar to the red-shift distribution of radio quasars of the same optical magnitude. Taking this into account and rounding things off somewhat, the following distribution for the red shifts of 18th-magnitude quasars was adopted for the subsequent analysis:

Red shift	1.58–2.51	20 percent
Red shift	1.00–1.58	35 percent
Red shift	.63–1.00	20 percent
Red shift	.40– .63	15 percent
Red shift	.25– .40	5 percent
Red shift	.16– .25	5 percent

The Sandage-Luyten survey had shown that in the entire sky there are, in round numbers, 20,000 quasars of apparent magnitude 18—just 1,000 times as many as in the new detailed sample.

RED SHIFT (Z)	SHELL VOLUME OF UNIVERSE (10^{27} CUBIC LIGHT YEARS)	NUMBER OF QUASARS IN WHOLE SKY: MAGNITUDE 17 CORRECTED DISTRIBUTION $\sim(1+Z)^6$	MAGNITUDE 17 IF UNIFORMLY DISTRIBUTED	MAGNITUDE 18 DERIVED FROM OBSERVATION
1.58—2.51	729			4,000
1.00—1.58	486	503	2,667	7,000
.63—1.00	295	1,026	4,249	4,000
.40— .63	146	660	1,980	3,000
.25— .40	61	560	1,253	1,000
.16— .25	22	202	361	1,000
.10— .16	7.3	219	332	
		3,170	10,842	20,000

DISTRIBUTION OF QUASARS according to red shift is shown for 20,000 quasars of 18th optical magnitude (*column at far right*), based on a representative sample of 20 quasars. The adjacent columns present two different estimates of the total number of quasars of the 17th magnitude. The method of making the estimates is explained in the illustration on the preceding two pages, where the same numbers appear in the diagrams labeled *b* and *c*. Observation shows that the number of quasars goes up by a factor of about six per magnitude rather than the factor of two expected if quasars were uniformly distributed throughout space. One can obtain the observed distribution by multiplying the shell volume of the universe by $(1+z)^6$, where z is the red shift and the exponent 6 is an experimentally determined value that yields the desired increment per magnitude. The table at top of these two pages shows the computed number and red shift of all quasars from magnitude 13 through 23.

RED SHIFT (Z)	SHELL VOLUME OF UNIVERSE (10^{27} CUBIC LIGHT YEARS)	SHELL VOLUME OF UNIVERSE X$(1+Z)^6$
1.58 —2.51	729	593,000
1.00 —1.58	486	74,600
.63 —1.00	295	10,900
.40 — .63	146	1,800
.25 — .40	61	336
.16 — .25	22	68
.10 — .16	7.3	15
.06 — .10	2.1	3.4
.04 — .06	.59	.8
.025— .04	.16	.19
.016— .025	.04	.05

TOTAL QUASAR POPULATION of universe is estimated to be on the order of 14 million, of which more than 99.7 percent are evidently fainter than the 18th magnitude and have red shifts greater than .4. From the 13th to 18th visual magnitude the number of quasars increases by a factor of five or six

If the 20,000 are distributed according to the percentages listed above, one finds that the number in each red-shift category, starting with the highest, is as follows: 4,000, 7,000, 4,000, 3,000, 1,000 and 1,000. It is clear that in a random sample of 18th-magnitude quasars more than half are extremely distant (red shift greater than 1) and therefore belong to the most luminous members of their class. A red shift of 1 corresponds to looking back two-thirds of the time that has elapsed since the universe began its expansion.

Proceeding to the next stage of the analysis, one would like to estimate the number of quasars whose apparent magnitude is either brighter or fainter than 18 and how they are distributed according to red shift. To do this one must know the volumes of the successive shells of the universe in which we have placed our 18th-magnitude quasars. These volumes depend on the cosmological model followed. Our unit of volume, 10^{27} cubic light-years, or a cube of which each side is a billion light-years, is co-moving, which means that no matter what the red shift, the unit of volume expands with the universe into our "local" unit of 10^{27} cubic light-years.

The 4,000 brightest and most distant quasars (red shift 1.58 to 2.51) occupy a shell with a volume of 729×10^{27} light-years. The problem now is to use this in-

APPROXIMATE VISUAL MAGNITUDE										
13	14	15	16	17	18	19	20	21	22	23
-	—	—	—	—	4,000	56,000	217,000	1,000,000	2,000,000	9,000,000
-	—	—	—	503	7,000	27,000	124,000	200,000	1,000,000	—
-	—	—	74	1,026	4,000	18,000	32,000	200,000	—	—
-	—	12	169	660	3,000	5,000	27,000	—	—	—
-	2	32	123	560	1,000	5,000	—	—	—	—
0	6	25	113	202	1,000	—	—	—	—	—
1	6	25	44	219	—	—	—	—	—	—
1	6	10	50	—	—	—	—	—	—	—
1	2	12	—	—	—	—	—	—	—	—
1	3	—	—	—	—	—	—	—	—	—
1	—	—	—	—	—	—	—	—	—	—
5	25	116	573	3,170	20,000	111,000	400,000	1,400,000	3,000,000	9,000,000

for each decline of one magnitude in brightness. Beyond the 18th magnitude, however, the increase is slower because the table contains no entries for quasars with red shifts greater than 2.51. In fact, only two quasars with larger red shifts are known, which suggests that there is a genuine paucity of such objects. Any quasar with a red shift of 2.5 is so distant that its light has been traveling through space for more than 85 percent of the age of the universe. The light from the more than 13.5 million quasars with a red shift greater than 1 has been en route for at least 6.8 billion years, assuming that the universe is on the order of 10 billion years old. Because the lifetime of a quasar is probably well under a billion years, the overwhelming majority of all the quasars that ever existed must have evolved by now into less luminous objects, perhaps ordinary galaxies. One can estimate that only about 35,000 quasars exist today.

formation to compute how many quasars of the same absolute luminosity would appear in the shell immediately within the outermost one, whose red shift corresponds to between 1 and 1.58. That shell, according to the cosmological model selected, has a volume of 486×10^{27} cubic light-years, or two-thirds of the volume of the outer shell. Now we introduce a supposition. If quasars were uniformly distributed in space, the inner shell would contain two-thirds times 4,000, or 2,667, quasars exactly like those in the outer shell. If quasars of that intrinsic luminosity were moved one shell closer to us, their apparent luminosity, as we observe them, would therefore be one magnitude brighter, that is, magnitude 17 instead of magnitude 18 [*see illustration on pages 58 and 59*]. Remember that the red-shift intervals were chosen specifically so that each step would correspond to a one-magnitude change in brightness.

A similar computation is now performed for the 18th-magnitude quasars in each of the other red-shift categories. In each case one computes the number expected in the shell within the preceding one, assuming as before that quasars are uniformly distributed in space.

This calculation yields the following additional numbers: 4,249, 1,980, 1,253, 361 and 332. When these are added to the number 2,667 previously computed, one obtains a total of 10,842 quasars of apparent magnitude 17, or roughly half as many quasars as one expects to find of magnitude 18 (assuming uniform distribution).

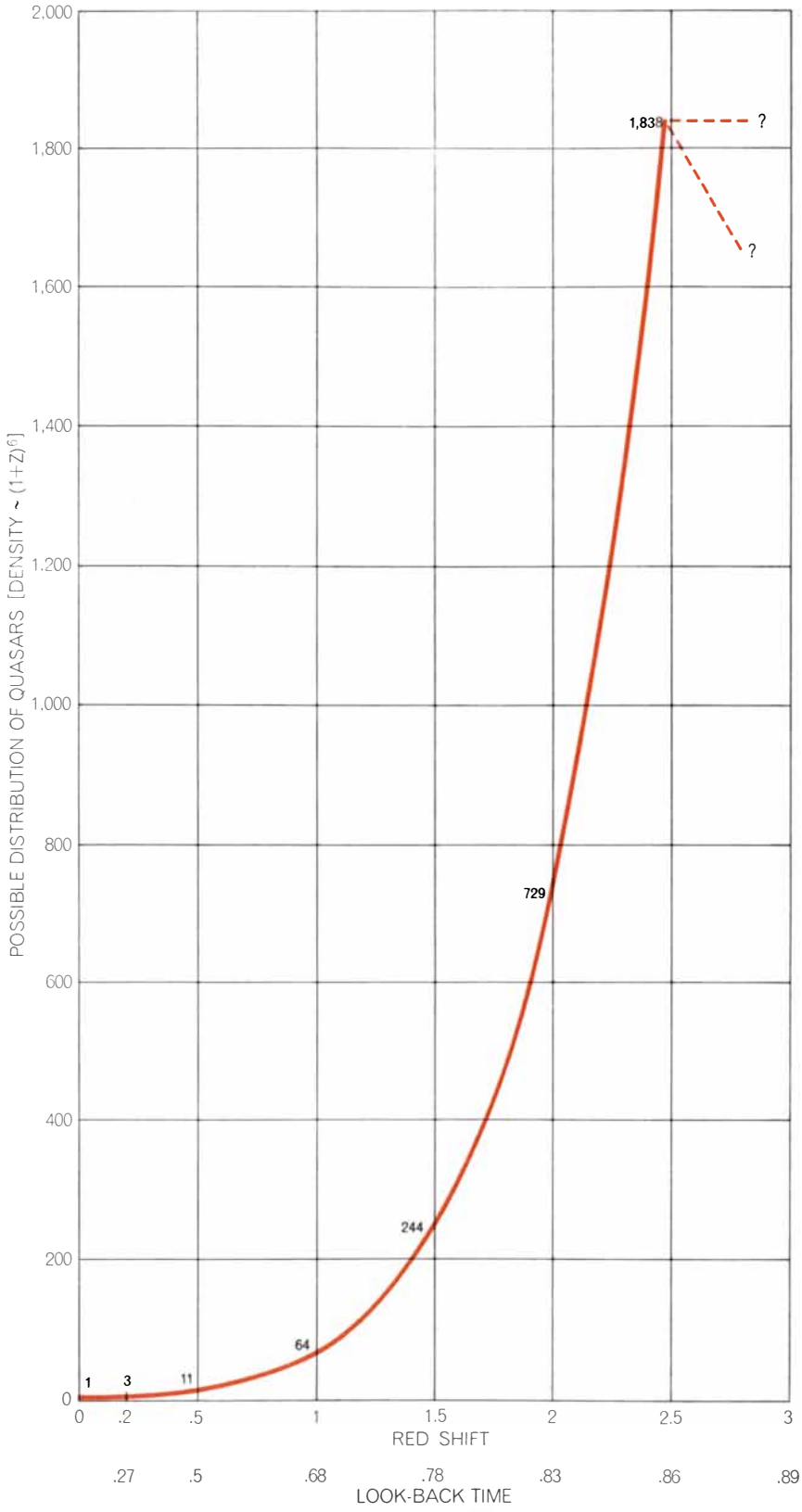
We recall that the Sandage-Luyten survey shows that the number of quasar-like objects increases not by a factor of two per magnitude (from 10,842 to 20,000 in the exercise just completed) but by a factor of about six. In other words, their statistics would predict only some 3,000 or 4,000 quasars of apparent magnitude 17 rather than 10,842.

What the factor of six tells us, of course, is that there are more faint quasars than one would expect to find if space were uniformly filled with quasars. The only plausible explanation is that the density of quasars must increase with increasing distance, that is, as we look back farther in time. To arrive at a distribution law that satisfies the observational evidence, let us assume that the density is proportional to some power, n, of the scale of the universe. The scale, or size, of the universe is inversely proportional to the amount by which light has been "stretched" by the expansion of the universe. Thus if the Lyman-alpha line emitted at 1,216 angstroms is observed at 3,648 angstroms, one can say that the universe has expanded by a factor of three since the radiation left the emitter. Since the red shift, z, in this case is 2 (3,648 minus 1,216 divided by 1,216) it is evident that the scale of the universe is given not by z but by $1 + z$. The density law we are seeking is therefore $(1 + z)^n$.

The value of n is simply obtained by trial and error to yield about 3,000 quasars of magnitude 17 [*see illustration on opposite page*]. Quite by accident the value of n turns out to be 6. It is only a coincidence that n is 6 and that the increase in the number of quasars per magnitude is also six. With this density law it is a simple matter to extend the distribution table downward from magnitude 17 and upward from magnitude 18 [*see illustration above*].

Along the bottom of the table one can read off the number of quasars expected in the entire sky for each magnitude. For the five magnitudes brighter than magnitude 18 the expected quasar population decreases steadily at each step from 3,170 (17th magnitude) to 573 (16th) to 116 (15th) to 25 (14th) and finally to five (13th). For the five magnitudes fainter than 18 the expected population rises steeply at each step from 111,000 (19th magnitude) to 400,000 (20th) to 1.4 million (21st) to three million (22nd) and finally to nine million (23rd). The total estimated quasar population from magnitude 13 to magnitude 23 inclusive is thus about 14 million.

The table does not list entries for



CHANGE IN QUASAR DENSITY WITH TIME can be derived from the table on the preceding two pages. The curve shows that the number of quasars rises steeply with increasing red shift, which is equivalent to looking back in time. Thus if one looks back 68 percent of the age of the universe, one would find more than 60 quasars in the volume of space that now contains one quasar. Looking back 83 percent of the age of the universe, one would find more than 700 quasars in the same volume. The maximum density may have existed when the universe had reached only about 14 percent of its present age. The scarcity of quasars with a red shift greater than 2.5 suggests that their density was no greater at earlier epochs.

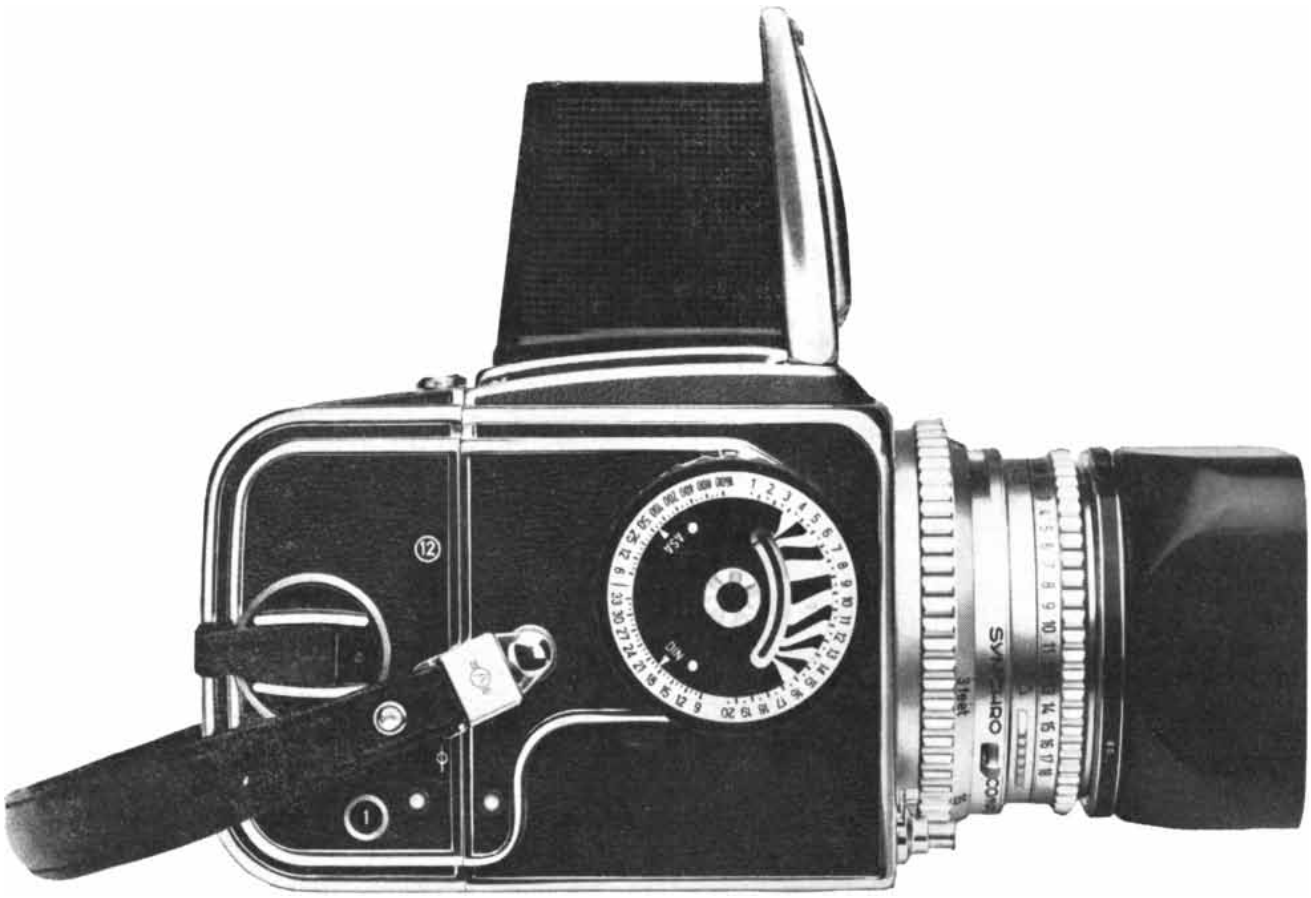
quasars with red shifts greater than 2.5. Actually two quasars with larger red shifts are known: one, PHL 957, has a red shift of 2.69; the other, 4C 05.34, has a red shift of 2.88. Their magnitudes are respectively 17 and 18. If the density law $(1 + z)^6$ continued to hold, one would expect a great many 19th-magnitude quasars with red shifts larger than 2.5. Their scarcity suggests that the density does not increase beyond 2.5 and that it may actually decrease.

The probable scarcity of quasars with red shifts greater than 2.5 implies that the largest telescopes are able to look back in time to the epoch when quasars made their first appearance in the universe. Depending somewhat on the cosmological model selected, one can say that the light from a quasar with a red shift of 2.5 began its journey through space some 8.6 billion years ago, or some 1.5 billion years after the big bang that hypothetically created the universe as we know it. Within the next few billion years the great majority of quasars were born and began their brief but brilliant career [*see illustration at left*].

One can estimate that the universe at present contains only some 35,000 quasars. All the rest have presumably evolved into less remarkable objects, perhaps ordinary galaxies; we know of their existence because the signals they emitted billions of years ago are only now reaching our telescopes. The quasars of the lowest intrinsic luminosity (those at the bottom of the table on the preceding two pages) are no brighter than large galaxies. It is therefore uncertain whether all of them are quasars or whether some are compact galaxies of one kind or another. To avoid such confusion one could consider leaving out the quasars listed in the two lowest (least luminous) categories all across the table. The remaining "high luminosity" quasars would then number about 1.5 million for the entire sky, and the number existing at the present time would drop to only 3,500.

Another way to look at the quasar population developed in this analysis is to compare the number of quasars with the number of galaxies in a given volume of space. A volume of 10^{27} cubic light-years in our neighborhood contains about 20 quasars, of which two are objects of high luminosity. In very round numbers the same volume of space contains probably between one million and 10 million galaxies.

The study described above involved quasars selected solely on the basis of their optical properties; their radio



The Company Camera

If one picture is worth a thousand words, you wouldn't know it to look at the average company.

The typical office fairly bulges with typewriters, copiers, dictating machines, dittos—everything to record and circulate the printed word.

But what about a camera for recording things visually?

Like that new product you want to publicize. And the construction of the new plant. And visiting dignitaries. And the faces of the stockholders when the company announces increased profits.

It's these things, captured on film, that breathe life into the annual report, brighten up the house organ and make for publicity releases that are more likely to get publicity.

So point number one: a good company camera should be able to be used by any member of the company, in any situation.

The Hasselblad is just such a camera.

It's a single lens reflex, which means you see exactly what you're taking at all times.

You view and focus on a brilliant interchangeable ground glass screen, rather than having to squint through a tiny peepsight.

You get big beautiful 2¼" x 2¼" pictures. Big enough to see all the results clearly, without having to enlarge or project them.

And most important for a company camera, the Hasselblad comes apart so you can put together new combinations.

You might want to change perspective. Take off the 80mm Carl Zeiss lens and put on the appropriate one. There are ten lenses in all, ranging from 40mm super wide angle to 500mm telephoto.

You may want to shoot a lot or a little. The 12-exposure magazine back comes off, so you can interchange it with any of four other backs that give you up to 70 exposures and a variety of formats.

You might want to make an audio-visual presentation using a standard 35mm projector. If so, just put on the 16S back and the same Hasselblad that gives you big 2¼" x 2¼" photographs will now give you superslides.

The backs also let you switch from black and white to color without first having to finish the roll. You can even put aside a partially exposed magazine to be finished at a later date. Without tying up the camera.

All these backs can be attached not only to the standard Hasselblad 500 CM, but to two other Hasselblad bodies as well. One is the electrically-driven Hasselblad. The other is a super-wide angle Hasselblad with 38mm lens attached.

Despite all the things it can do, the Hasselblad is one of the simplest cameras to operate.

Simplicity was one of NASA's requirements in choosing a camera to be used in space. (After all, the astronauts aren't professional photographers. And they had to operate the camera with bulky gloves on.) As it turned out, Hasselblad not only became the space camera, but went on to reach the moon.

Lastly, Hasselblad is a sturdy camera. Which equips it for survival in a variety of hands. Some less gentle than others.

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The System

emission, if any, is negligible. It is therefore important to ask if quasars selected on the basis of their radio luminosity also show an increase in density with increasing distance. The 3C catalogue mentioned above is a comprehensive listing of all radio sources in the northern half of the sky with a certain minimum radio intensity. (The minimum value is nine "flux units" at 178 megahertz, or 9×10^{-26} watt per square meter per hertz.) By the late 1960's 44 of the 300-odd extragalactic radio sources in the 3C catalogue had been optically identified as quasars. Of these 44 objects 33 had optical magnitudes of 18.5 or greater, and there was reason to believe that the 33 represented essentially all the 3C quasars down to that limiting magnitude.

Radio-bright Quasars

The analysis of the distribution of the 33 objects is complicated because both a radio limitation and an optical limitation were involved in their selection. That is to say, to appear in the group of 33 quasars an object had to radiate strongly in two widely separated parts of the spectrum: the radio region and the optical region. The analysis made by one of the authors (Schmidt) went as follows:

From the red shift the distance to each object was computed on the basis of some particular model of the expanding universe. This distance equaled the radius of the volume of space within which the object was actually observed. One can then ask how far the object could be moved outward before one of two things happen: either its apparent magnitude drops below 18.5 or its radio flux falls below nine units. This distance defines the radius of the maximum volume beyond which the object could not lie and still remain a member of its original class.

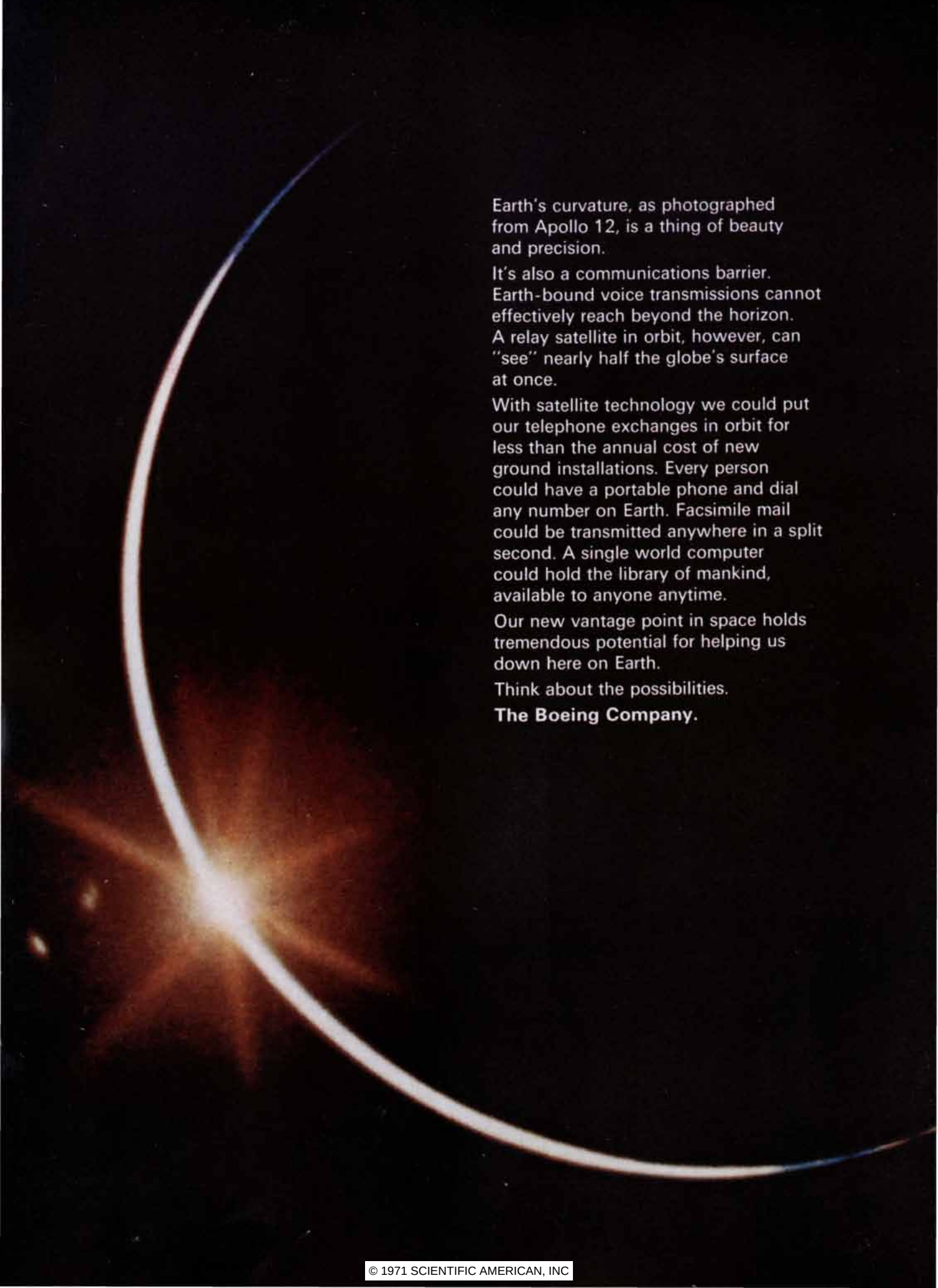
For each object one can express the ratio of the two volumes, actual volume over maximum volume, as a decimal fraction. A priori, if the 33 objects were uniformly distributed, one would expect the average value of this fraction to be .5. Thus one would expect half of the values to be less than .5 and the other half to lie between .5 and 1. Actually only six of the objects yield values below .5 whereas 27 give higher values. In other words, radio quasars tend to occupy the outer reaches of the volume within which they can be observed. This tells us that their density increases with distance. When the density law is worked out in detail, it is found to lie between $(1 + z)^5$ and $(1 + z)^6$. That is remarkably similar to the density law obtained for optically selected quasars, which on the average show negligible radio emission. The conclusion is that quasars have a density distribution that is only slightly or not at all dependent on their radio properties. This still leaves unsettled, however, the two possibilities already mentioned: either most quasars pass through a brief evolutionary stage during which they emit strongly at radio wavelengths or else only a small fraction of all quasars are destined to evolve into strong radio emitters.

Other Quasar Hypotheses

A number of astronomers and theorists originally found it difficult to accept the idea that the red shifts of quasars are cosmological. They did not see how it was possible for an object to emit as much light as 100 galaxies and yet vary in intensity by 10 percent or more in a few days. They proposed, as one alternative, that quasars might be much nearer and smaller objects ejected at high velocity from the center of our own galaxy. This is sometimes called the local-Doppler hypothesis because the red shift is a Doppler shift and the objects are of local origin. Being only a few million light-years away, rather than billions of light-years, their actual energy output would be much less.

This hypothesis has encountered the difficulty that quasars are much more numerous than anyone suspected in the early 1960's. As we have just seen, recent estimates run into the millions, and on the most conservative basis one can hardly assume fewer than a million quasars. It may be estimated that the mass of the typical quasar, on the basis of the local-Doppler hypothesis, would have to be at least 10,000 suns. The ejection of a million objects, each of 10,000 solar masses, from the center of our galaxy would require that the mass of all the stars in the galactic nucleus be completely converted into energy. One must also explain why the only quasars ever observed are those ejected by our own galaxy. If any quasar-like objects had been ejected by any of the scores of galaxies in our immediate neighborhood, some of them should be observed to be heading *toward* us and thus should exhibit a blue shift rather than a red shift. Yet no quasar-like object with a blue shift has ever been detected. The local-Doppler explanation, on the whole, must be regarded as being quite unlikely.

A totally different explanation for the



Earth's curvature, as photographed from Apollo 12, is a thing of beauty and precision.

It's also a communications barrier. Earth-bound voice transmissions cannot effectively reach beyond the horizon. A relay satellite in orbit, however, can "see" nearly half the globe's surface at once.

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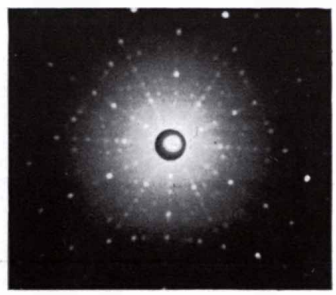
Our new vantage point in space holds tremendous potential for helping us down here on Earth.

Think about the possibilities.

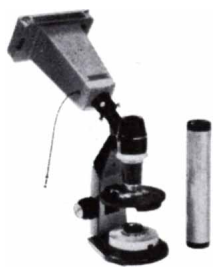
The Boeing Company.

Recording wonders in seconds is one of the wonders.

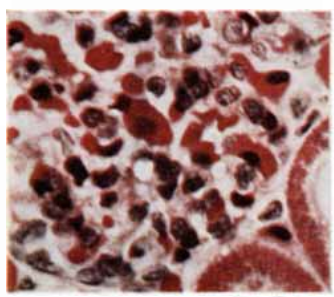
XR-7 FOR X-RAY CRYSTALLOGRAPHY



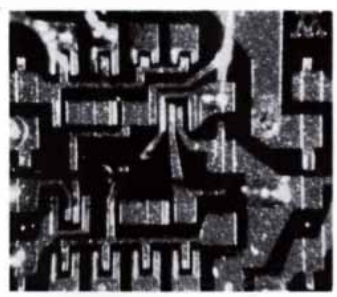
Diffraction pattern, sapphire



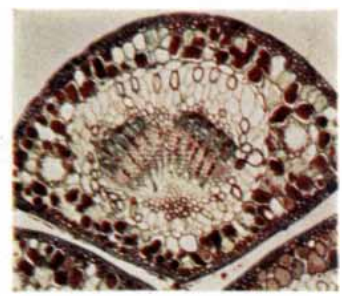
ED-10 FOR PHOTOMICROSCOPY



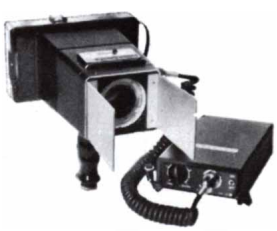
Section, mouse kidney, 1000x



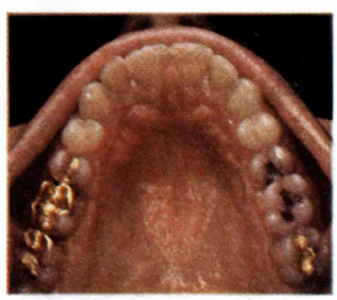
Integrated circuit, 80x



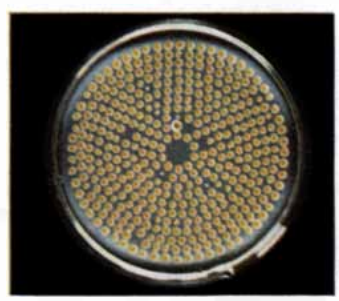
Pinus leaf section, 100x



CU-5 FOR CLOSE-UPS

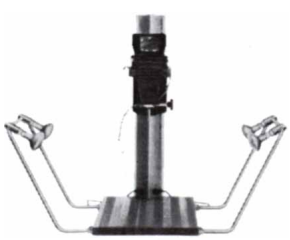


Clinical dental record



Macrophotograph, bacteria colonies

Immunoelectrophoresis

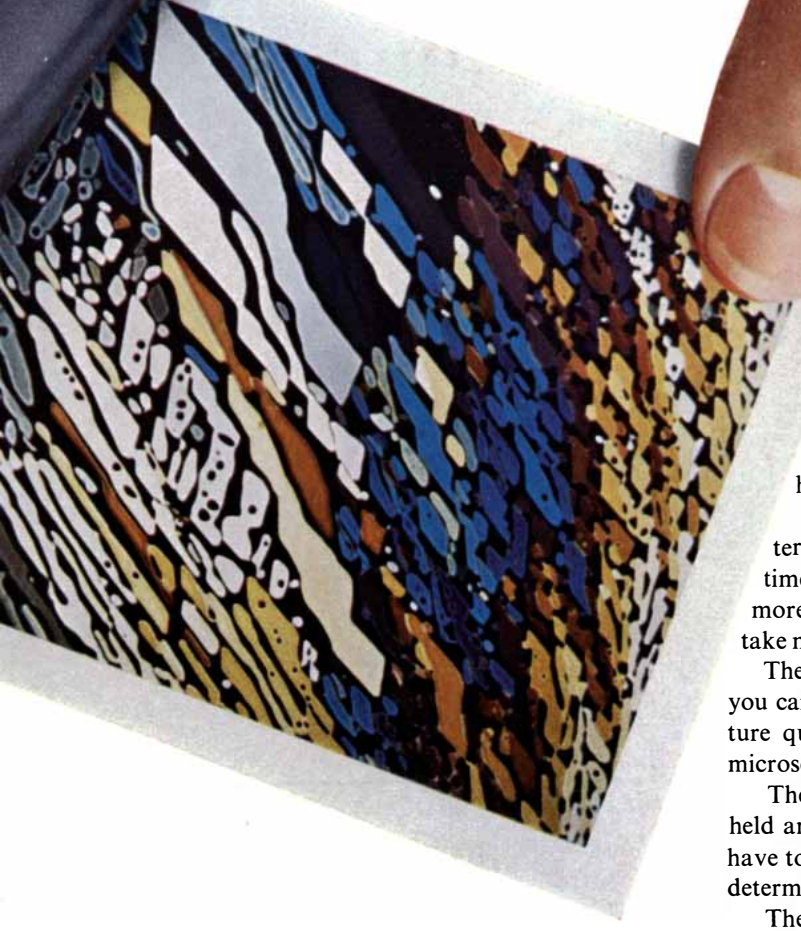


MP-3 MULTIPURPOSE

High contrast copy, continuous-tone art

Macrophotograph, diode fractures

Fingerprint record, negative



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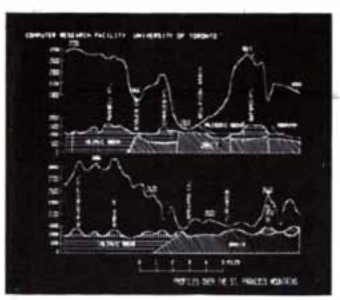
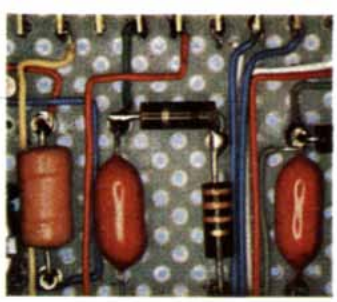
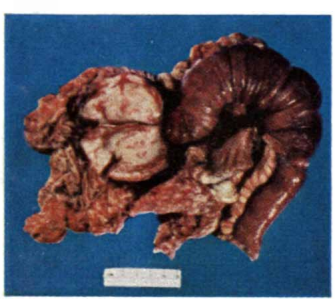


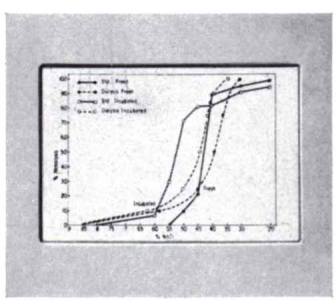
Hard copy, computer terminal display



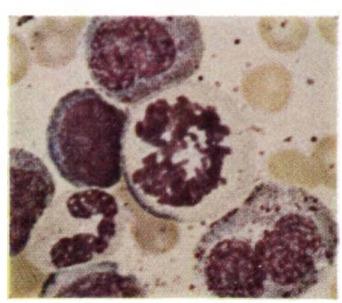
Electronic components



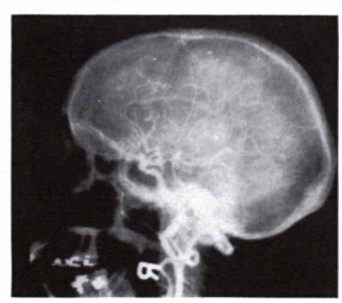
Gross specimen, intestinal fibroma



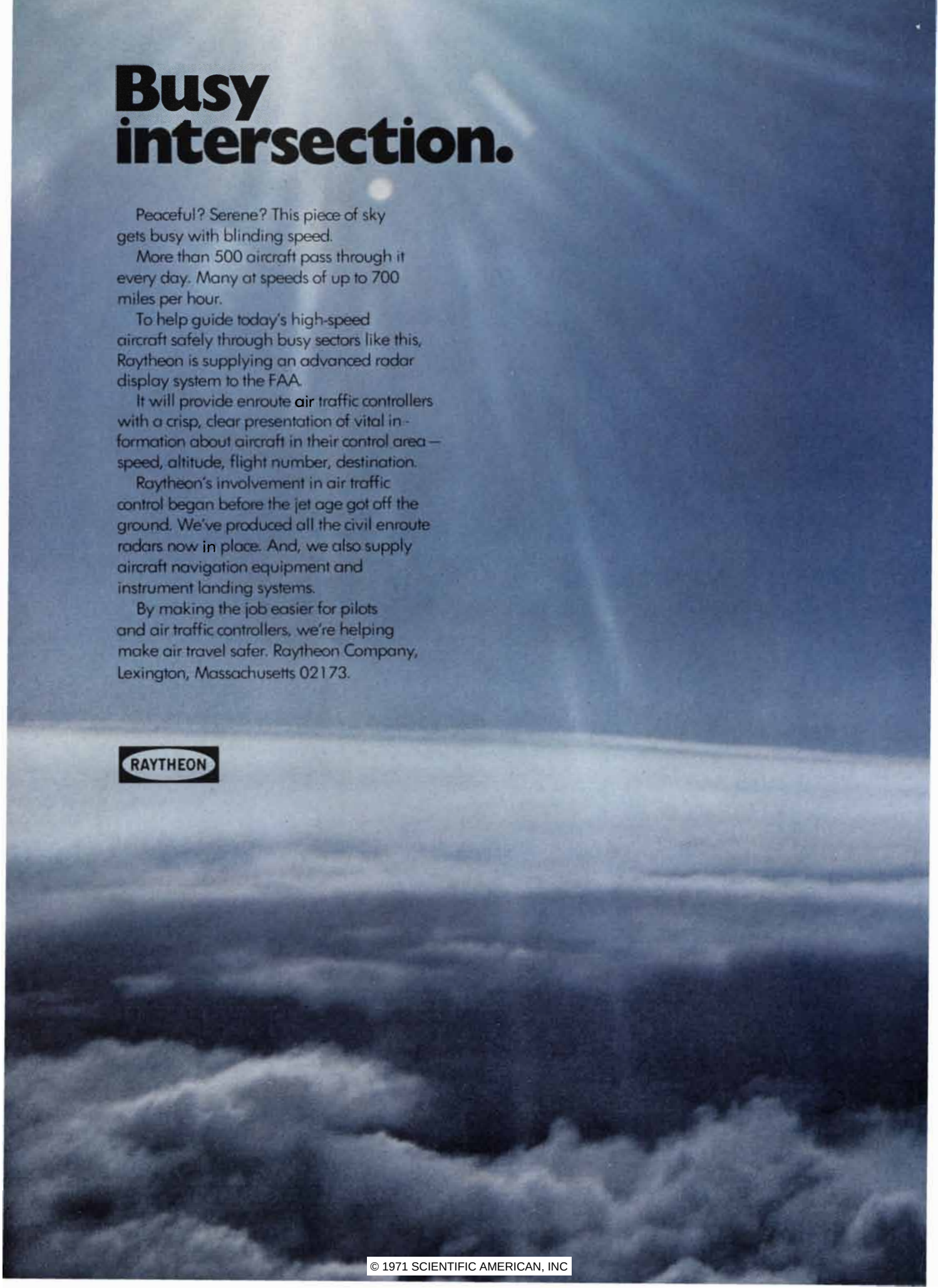
Graph for presentation, 35mm



Human leukemia, 1600x



X-ray copy



red shift of quasars seemed attractive at first. According to this hypothesis quasars are objects in which a substantial mass is compressed into an extremely small volume. Light emitted from such an object would have to overcome an immense gravitational potential and would be red-shifted just as it is in quasars. The physical conditions that the hypothesis must account for can be rather precisely calculated. It is possible to compute, therefore, how large an emitting envelope of gas is needed, and what its density and temperature must be, to produce the spectral lines actually observed in quasars.

But if one assumes, to take an extreme case, that the highly condensed mass is comparable to the mass of the sun, its emitting envelope would not exhibit the required luminosity unless it were within 10 kilometers of the observer! The object has to be more distant, of course, and that will require a larger mass. The masses computed are large, and thus tend to create inadmissible side effects. For example, at a distance of 30,000 light-years the mass would have to be 10^{11} suns; it would rival the mass of our own galaxy, whose center is at the same distance. If the mass is raised still further to 2×10^{13} suns, the minimum distance can be raised to 10 million light-years. In that case, in order not to raise the observed average density of the universe, a million such quasars would have to be distributed out to a distance of at least a billion light-years, at which point they would hardly qualify any longer as local objects.

One other "anticosmological" hypothesis should be mentioned for the sake of completeness: the hypothesis that the cause of the quasar red shift is simply unknown and thus lies outside present-day physics. Since no arguments can be made against such a metaphysical hypothesis it cannot be excluded.

The Cosmological Hypothesis

An attractive feature of the cosmological hypothesis is that the quasar red shift comes "free," without requiring the introduction of bizarre physical conditions to explain the shift. The quasars exhibit a red shift simply because they are being carried along by the expansion of the universe. The extraordinary luminosity of quasars, together with their short-term variability, originally constituted the strongest objection to the cosmological hypothesis. In the past five years, however, short-term luminosity fluctuations of considerable magnitude have been observed in the nuclei of two rather special kinds of galaxy: N-type galaxies and Seyfert galaxies. These nuclei are starlike and resemble quasars in producing an excess of ultraviolet radiation. Moreover, there is general agreement that their red shifts, even though they are modest in the case of Seyfert galaxies, are cosmological in origin.

Recently it has been found that both quasars and Seyfert galaxies radiate strongly in the infrared region of the spectrum. Indeed, the infrared luminosity of the nearby Seyfert radio galaxy 3C 120 is 10^{46} ergs per second, which is equal to the infrared luminosity of many quasars when their luminosity is calculated on the assumption of their being at cosmological distances. In other words, we now have examples of objects whose extraordinary energy output is as difficult to explain as the output of quasars (regarded as cosmological objects) and whose output varies over time scales that are just as brief as the time scales for the variation of quasars. Therefore the cosmological hypothesis cannot be ruled out on the basis of the difficulties encountered in explaining the quasars' rapidly varying high luminosity, because the same difficulties hold for galaxies whose properties and distances are not in question.

Support for the cosmological hypothesis has recently been obtained by James E. Gunn of the Hale Observatories. He found that the image of the quasar PKS 2251 + 11 (red shift .323) is superposed on the image of a small, compact cluster of galaxies. Gunn was able to determine the red shift of the brightest galaxy in the cluster and found a value of .33 ± .01. The coincidence in direction and red shift makes it very likely that the quasar is associated with the cluster of galaxies, thus confirming the cosmological nature of its red shift.

As for the ultimate source of the tremendous energy observed in quasars, there has been no lack of hypotheses, among them stellar collisions, the gravitational collapse of massive stars, supernova explosions, conversion of gravitational energy into particle energy by magnetic fields, matter-antimatter annihilation and the rotational energy of a very compact mass (as proposed for pulsars). There is also no agreement about the radiation mechanism, particularly in the infrared, where much of the output is radiated. Similar problems exist for nuclei of galaxies, notably for those of Seyfert galaxies. The solution of these problems constitutes one of the main challenges to present-day astronomy.

COOLING TOWERS

Hot water carrying waste heat from a large industrial installation such as a power plant is often best handled by a tower that breaks the water up, cools it in a cross draft of air and then recirculates it

by Riley D. Woodson

A modern steam-turbine electric power plant has a thermal efficiency of about 40 percent, meaning that 40 percent of the heat energy put into the system by the burning of fuel emerges from the plant as electrical energy. Most of the remaining heat has to be eliminated as waste. In the majority of such plants the heat is removed by drawing water from a stream or a lake or even a body of salt water, running it through the plant once and then returning the heated water to its source. This type of cooling is becoming less acceptable as questions arise about the adequacy of cooling-water supplies and about the biological effects of warming natural bodies of water.

What are the alternatives for cooling power plants and other industrial facilities? Air is a perfectly good coolant, and indeed a few plants are cooled by "dry" systems. Since air is a gas, however, one must move huge volumes of it and provide elaborate heat-exchange surfaces in order to cool a large plant effectively. A more practical alternative is the "wet" cooling tower, where both air and water serve as coolants. In such a tower the cooling water being circulated through a plant falls through a draft of air and heat is carried away mostly by evaporation. The rest of the water is collected at the bottom of the tower and returned to the cooling cycle.

Although the principle is simple, the tower itself is likely to be quite an elaborate structure. One reason is the large amount of heat that must be removed from many industrial plants. Another is the need to pass the water through the tower in the form of fine droplets in order to achieve maximum contact between the water and the air. As a result a typical tower of a kind now in service, incorporating high-capacity fans to assist the flow of air, is about 55 feet wide at the bottom, 75 feet wide at the top and 325 feet long; it consists of several cooling cells, each with a draft fan as large as 28 feet in diameter powered by a 200-horsepower motor. The chimney-like natural-draft towers that are more common in Europe than in the U.S. can be 300 feet or more in diameter at the base and as high as 500 feet. If one thinks in terms of a fossil-fueled power plant with a capacity of 800,000 kilowatts, the cost of an adequate mechanical-draft tower would be about $1.7 million and of a natural-draft tower about $4.2 million. The cost of operating the natural-draft tower would be lower, however, since such a structure acts as a chimney and does not need electric power to drive fans.

Cooling towers of much smaller scale, such as the ones used in central-air-conditioning systems, are usually factory-built, bought from a catalogue and installed as a component of a building. The large-scale cooling towers of the kind found at generating stations, petrochemical plants and other major industrial operations are designed individually and built at the site.

The designer of a large cooling tower must deal with a variety of physical factors. He needs to know what the temperature of the water will be when it enters the tower and what temperature it should be when it leaves the tower. The difference between them defines the cooling range of the tower. In general the range is between 10 and 40 degrees Fahrenheit.

Another factor to be considered is the normal summertime temperature of the area where the tower is to be built, since the cooling problem increases with higher ambient temperature. For this calculation one uses the "wet bulb" temperature of the environment rather than the temperature recorded on a standard dry thermometer. The wet-bulb temperature is the lowest water temperature that can be realized by evaporation into the surrounding environment. It is measured by whirling a thermometer whose bulb is covered with wet cloth, and it represents

FOUR COOLING TOWERS serve the Keystone Steam Electric Station in western Pennsylvania. Each pair of towers serves one of the station's two 820,000-kilowatt gen-

the theoretical limit of cooling that a tower can achieve. To attain it would require a tower with a thermal efficiency of 100 percent, which in practice is beyond reach.

The difference between the theoretical limit and the actual cooling accomplished by a tower is called the tower's "approach to wet bulb." The approach is seldom closer to the theoretical limit than five degrees F., and more often it ranges between seven and 15 degrees. The wet-bulb temperatures for which cooling towers are designed vary from 60 to 83 degrees F. The usual criterion is that the tower's designed wet-bulb temperature is exceeded no more than 5 percent of the total summer operating time of the tower.

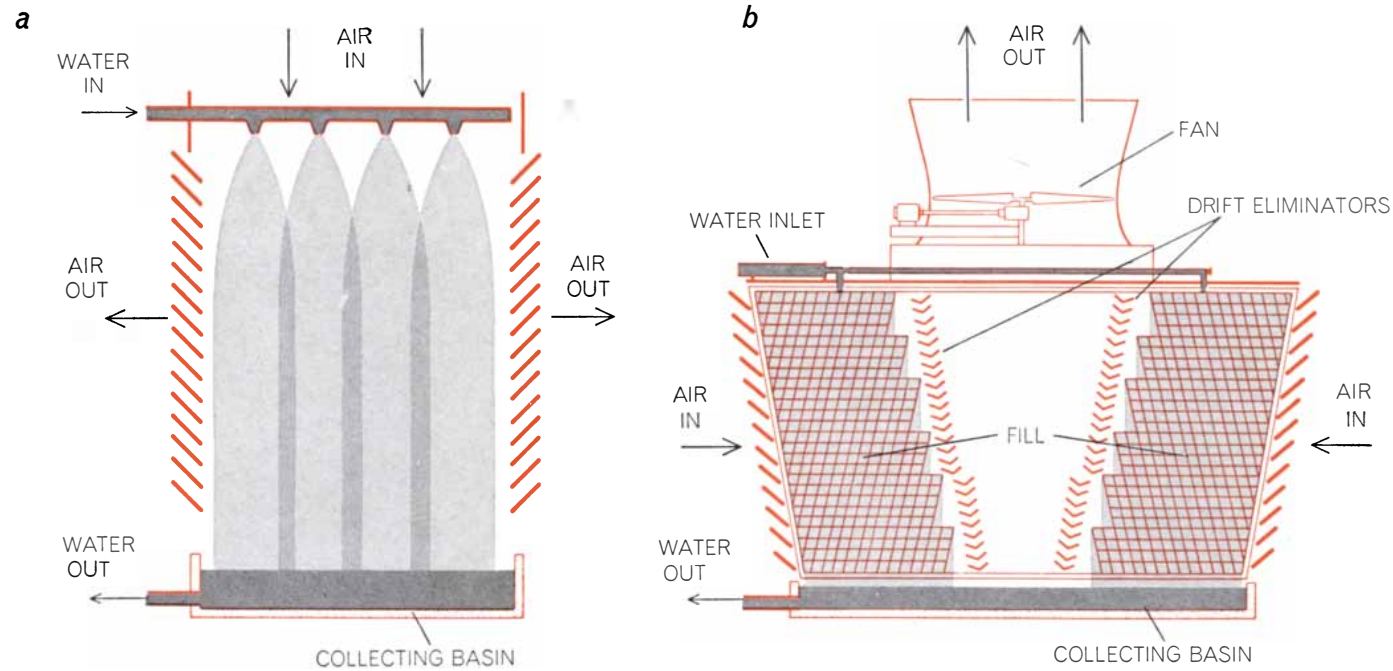
Since the cooling is mainly evaporative, part of the water circulating through the system is lost by evaporation. The rule of thumb is 1 percent of evaporation loss for each 10 degrees F. of cooling. There are two other sources of water loss. The first is drift, meaning water that is simply carried out as very fine droplets with the air leaving the tower. The cooling-tower industry routinely guarantees that the loss by drift will not exceed .2 percent of the water circulated. The second source of loss results from the need to bleed off part of the water in order to get rid of dissolved solids that might form scale and interfere with the operation of the system. In the industry this process is called blowdown. As a rule it amounts to about .3 percent for each 10 degrees F. of cooling.

The sum of these losses has to be made up by adding water to the system. Although the losses are only a small percentage of the total water flow, the amount of water required for "makeup" in a large cooling tower is considerable. In a modern 680,000-kilowatt generating plant the amount of water circulating through the tower units under average summer conditions would be about 345 million gallons per day and the requirement for makeup would be about 6.5 million gallons per day.

The first industrial cooling towers, which were built early in this century, depended on the natural movement of air. Since natural wind is seldom strong enough to produce a brisk movement of air across a wide structure, such an atmospheric tower had to be long, narrow and high and built broadside to the prevailing wind. Decks were built at intervals inside the tower to break up the falling water. The towers entailed no cost for mechanical equipment, but because they were high and the water to be cooled had to be pumped to the top, the pumping costs were fairly substantial. Moreover, the amount of cooling accomplished by an atmospheric tower with a given amount of water was erratic because it depended not only on the environmental temperature but also on the speed and direction of the wind.

The modern counterpart of the atmospheric tower is the hyperbolic tower, which operates on the natural-draft principle. The term "hyperbolic" refers to the fact that the tower characteristically

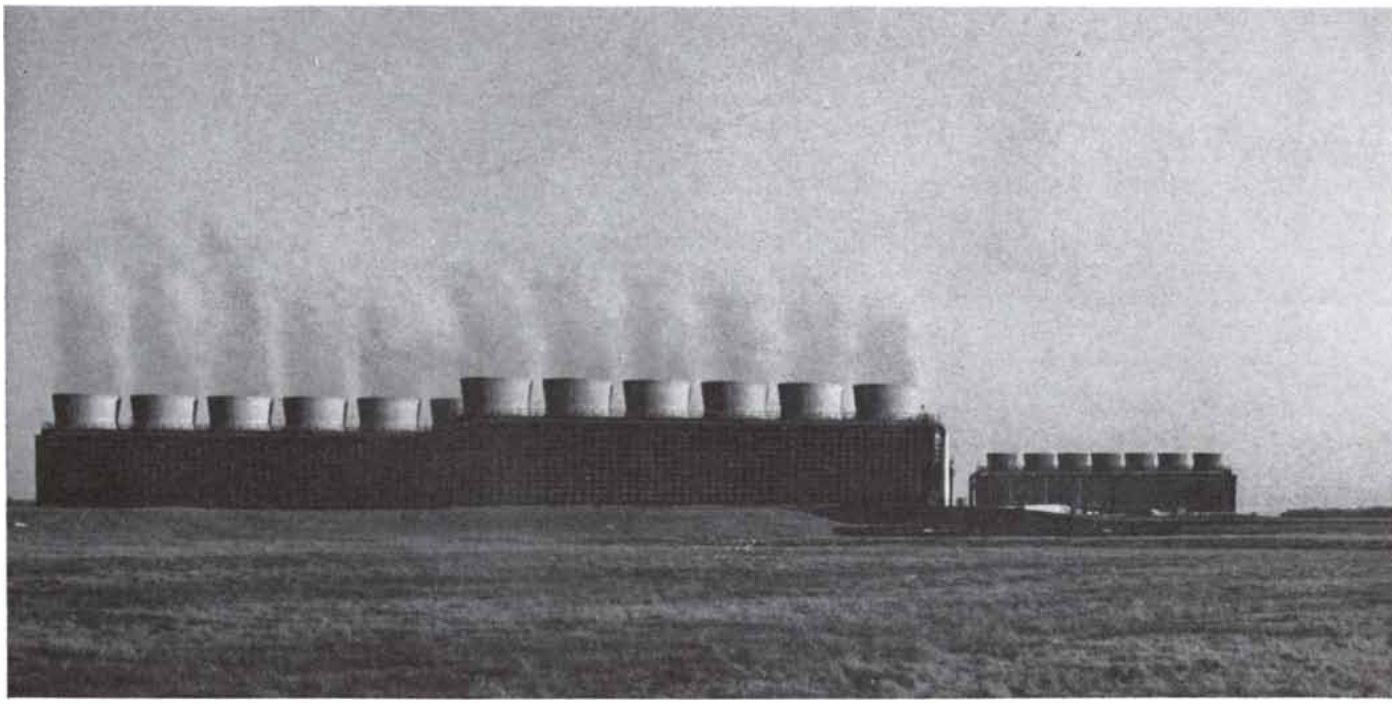
erating units. The towers are 325 feet high, 247 feet in diameter at the base and 142 feet in diameter at the top. They are natural-draft towers of typical hyperbolic form, with most of their height functioning to help induce a strong draft of air that moves up the inside of the tower as warm water from the plant falls through the draft near the bottom of the tower. Clouds of vapor emerge from the towers at left; two towers at right were not operating when photograph was made. Plant is jointly owned by seven electric utilities.



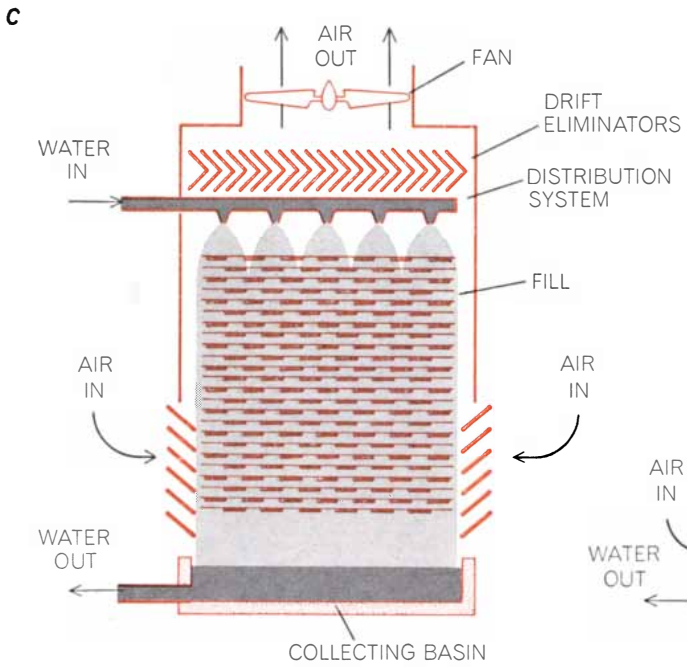
TYPES OF TOWER are depicted schematically. The atmospheric tower (*a*), which was one of the earliest types of cooling tower, relied on natural winds and the aspirating effect of the spray nozzles to provide cooling air. The mechanical-draft crossflow tower (*b*), which is the kind in widest use at present, has a fan at the top to draw air in through the louvers, across the path of the falling water and out of the stack. "Fill" is the material that breaks up water into fine droplets; the drift eliminators retard the movement of

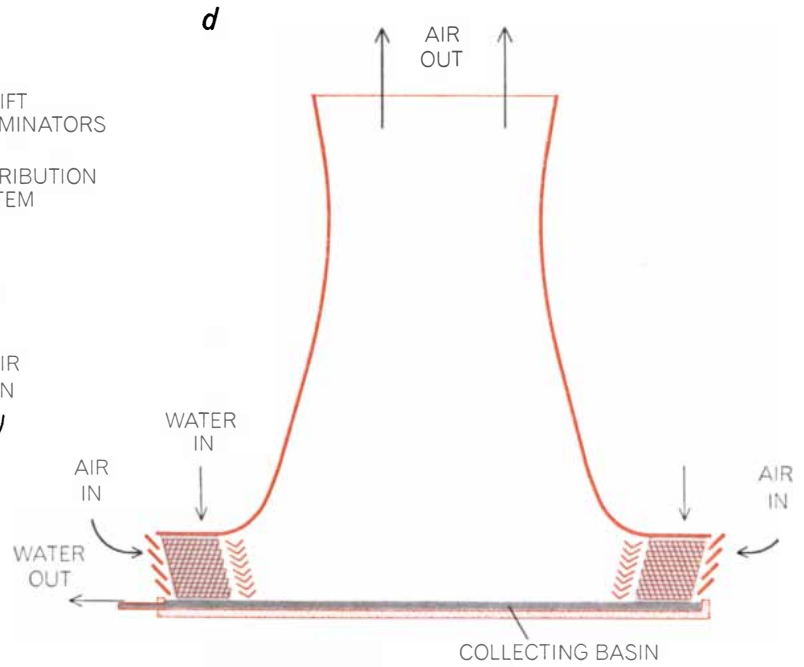
has the form of a hyperbola [*see illustration on preceding two pages*]. In such a tower air moves upward as a result of the chimney effect created by the difference in density between the warm, moist air inside the tower and the colder, denser air outside. Hyperbolic towers are best suited to regions with high humidity, such as western Europe and parts of the eastern and northwestern U.S. They are also desirable in populated areas because the height of the exhaust from such a tower helps to prevent the formation of fog along the ground.

Economic reasons as well as climatic ones account for the greater prevalence of hyperbolic towers in Europe. A hyperbolic tower is usually built of thin-shell reinforced concrete, and its construction calls for much labor, which costs less in Europe than in the U.S. The cost of elec-



MECHANICAL-DRAFT CROSSFLOW TOWERS serve the 640,000-kilowatt power plant of the Northeastern Station of the Public Service Company of Oklahoma. One cell of one tower is shown on the cover of this issue. In all the plant is served by two six-cell

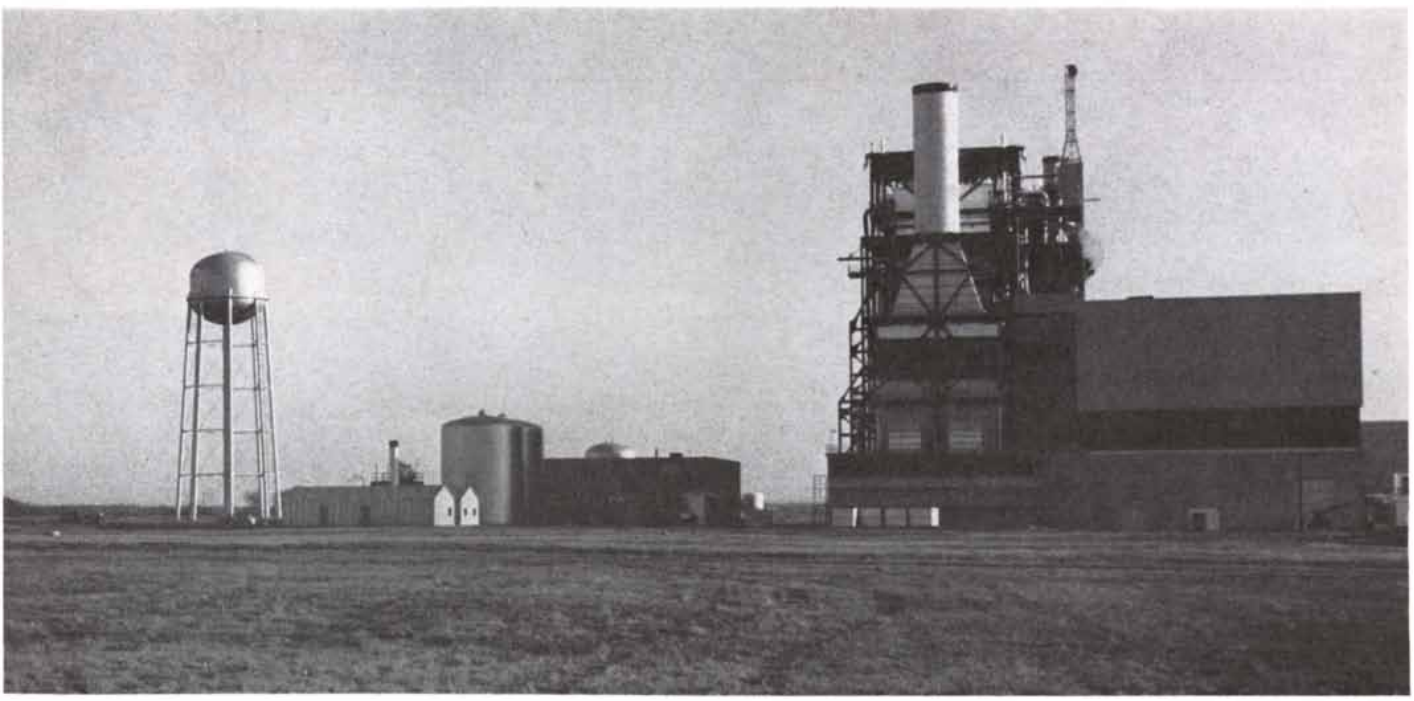




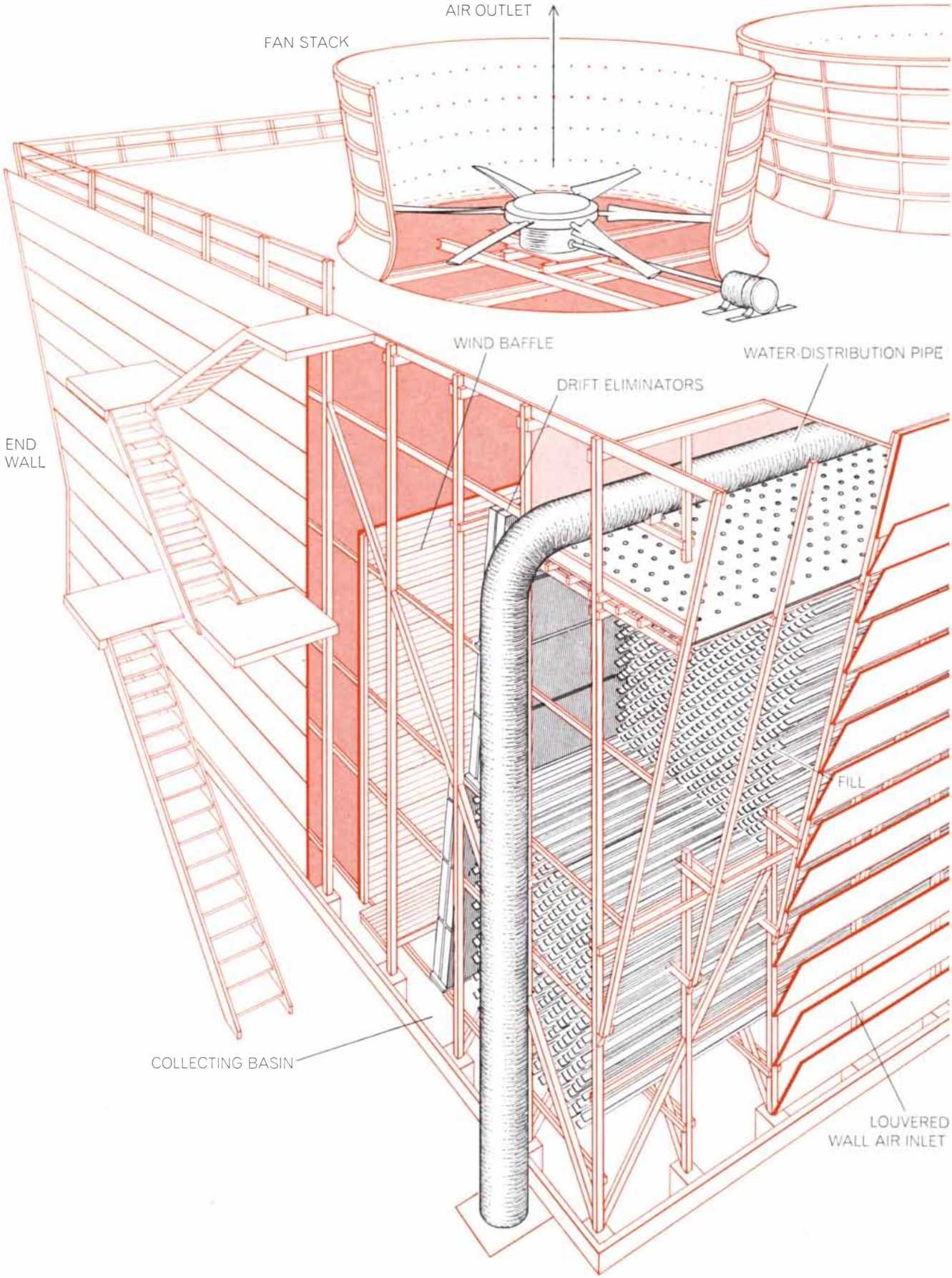
water out of the stack with the departing air. The towers shown on the cover of this issue and in the photograph at the bottom of these two pages are of this type. The mechanical-draft counterflow tower (*c*) is similar except that the air moves vertically upward through the falling water. The hyperbolic natural-draft tower (*d*) has no fan; the draft results both from the height of the structure and the difference in density between the warm, moist air inside the tower and the colder, denser air outside. Discharge is far above ground.

tric power, however, is higher in Europe, and so it is advantageous to be able to operate a cooling tower without a fan. In recent years conditions have changed, so that more hyperbolic towers are being built in the U.S. The reasons include improved materials and building techniques, the rising cost of land (a hyperbolic tower takes less land than other types) and the effectiveness of the hyperbolic tower in dissipating large quantities of water vapor.

Mechanical-draft towers, using fans to either force or induce the movement of air, first came into use about 40 years ago. In a forced-draft tower the fan is at the bottom and pushes the air up through the tower; in an induced-draft tower the fan is at the top and pulls the air up. The forced-draft regime creates several problems in large-scale towers,



towers, which are in the foreground at left, and two seven-cell towers, which are in the background at left. The generating station is at right. In normal operation the flow of water through the entire set of four cooling towers is about 523 million gallons per day.



DETAILS OF CONSTRUCTION are depicted for one cell of a mechanical-draft crossflow tower. Ordinarily much of a tower is made of wood, although plastic is coming into use for the slatlike members that constitute the fill. In this design the large pipe near the top, which distributes the hot water that will fall through the tower to the collecting basin, is made of plastic reinforced with glass fiber. The tower is louvered on two sides to admit the cooling air that flows across the falling water. The two end walls are solid.

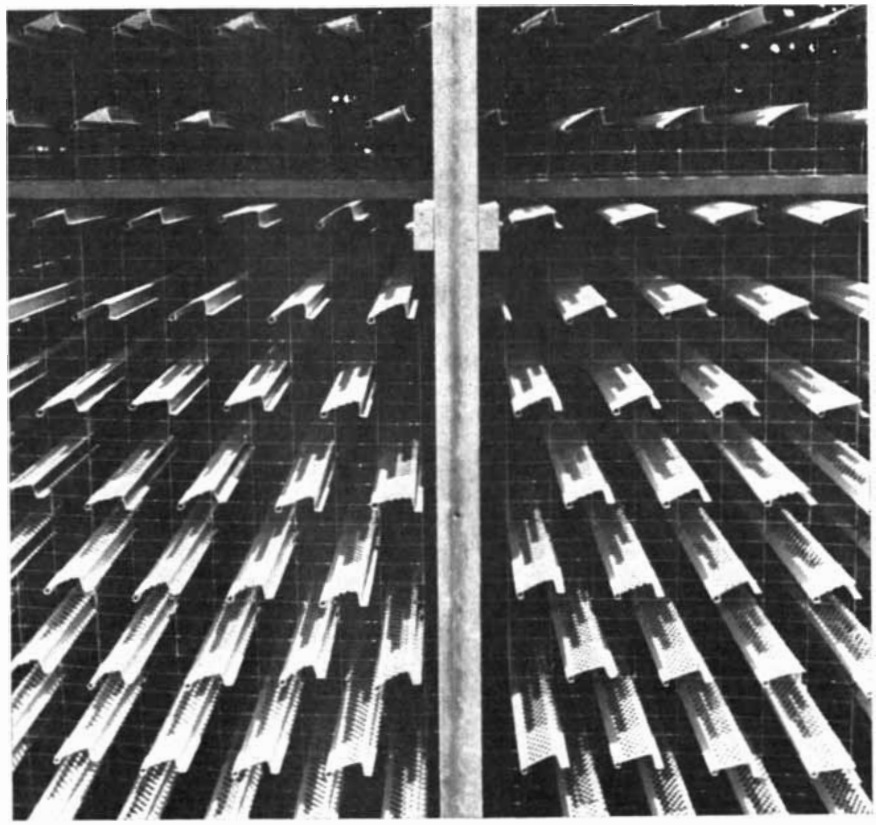
chief among which is recirculation: vapor leaving the tower at low velocity tends to reenter the tower. As a result the wet-bulb temperature of the entering air is increased and the performance of the tower is impaired. Another problem is that the uniform distribution of air through the tower that is necessary for efficient operation is difficult to attain in large forced-draft units. For these reasons modern mechanical-draft towers of industrial size operate on the induced-draft principle.

Depending on the particular requirements for a mechanical-draft tower, the designer will arrange for either a counterflow or a crossflow movement of the air past the falling water. In a counterflow tower the water moves down and the air moves up; in a crossflow tower the water moves down and the air moves horizontally. For a number of reasons the crossflow principle is much more widely used than the counterflow principle.

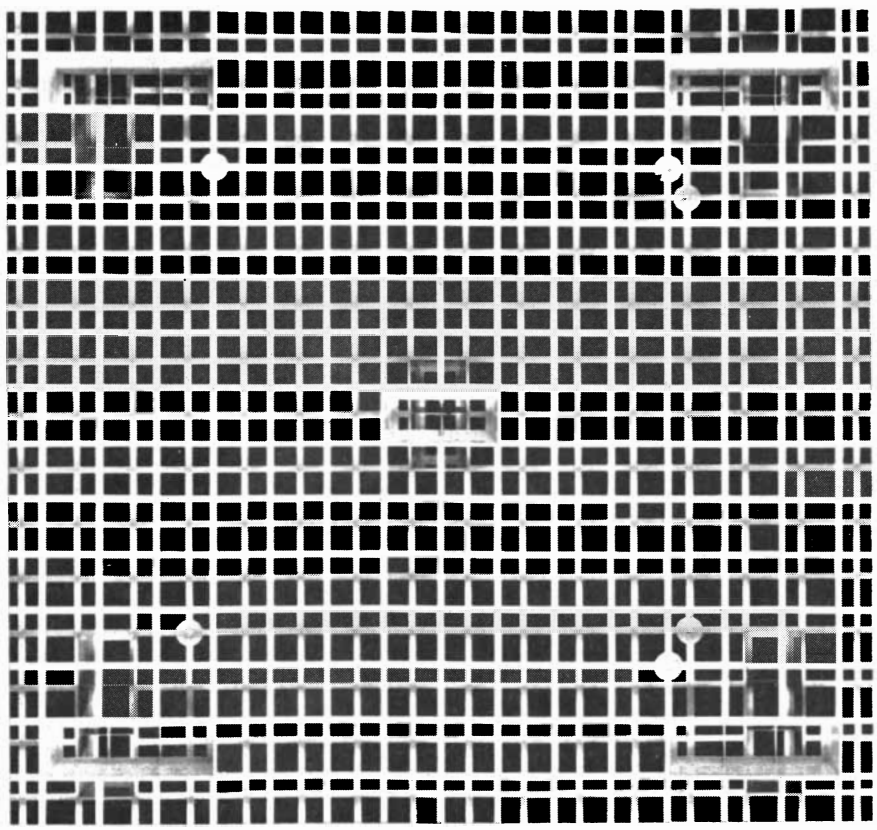
A distinct advantage of the crossflow design is its low loss of draft. In a counterflow tower the air travels all the way from the bottom to the top, passing through all the water and meeting greater resistance from it. A significant loss of draft results. In a crossflow tower the air cuts across the path of the water and travels a shorter distance vertically, with a lower loss of draft.

Another consideration favoring crossflow towers stems from the fact that the cooling performance of a tower rises with increased height of "fill": the material in the tower that breaks up the water into fine droplets. The crossflow tower benefits particularly from increased height because the distance the air travels is independent of fill height. Therefore the distance the air travels and the height of the fill (or the distance the water travels through air) can be adjusted to minimize the loss of draft. In a counterflow tower the distance the air travels varies directly with the fill height, so that the fill height can be increased only at the expense of increasing the horsepower of the fan to compensate for the greater loss of draft through the fill. The crossflow tower is superior to the counterflow tower in handling heavy loads of water with long cooling ranges and close approaches to the wet-bulb temperature.

In "dry" cooling towers, where air alone is the ultimate coolant, the water that holds the heat removed from the plant is circulated through a closed system of tubes exposed to air. Such a tower, operating without losses of water from evaporation and drift, is advantageous in areas where the supply of



SPLASH-BAR FILL is usually installed in large cooling towers. Laid horizontally to a considerable depth in the tower, the bars interrupt the fall of the water, causing it to break up into fine droplets. Bars are usually made of wood or, as in this case, perforated plastic.



FILL OF FILM TYPE is sometimes used in smaller towers. It is made in geometric shapes that cause the falling water to form many surfaces and thus gain more exposure to air.

water is limited. The towers are very costly, however, and so they have been built only at a small number of generating stations with special needs. Most of the dry units are outside the U.S. and at generating stations of relatively small size (250,000 kilowatts or less).

In a wet tower the heated water entering the top of the tower for cooling is distributed evenly for its fall through the tower. In most crossflow towers the water simply pours over baffles that break up the flow into droplets. In counterflow towers, however, it is difficult to achieve uniform distribution of water by gravity, and so pressure is supplied to start the water downward as a spray emerging from nozzles.

The distribution system functions in the highly corrosive oxidizing atmosphere of the tower. Accordingly the materials for the system must be chosen with care. Piping made of redwood, cast iron, galvanized steel and, more recently, plastic is installed in order to keep down maintenance costs.

Water coming out of the distribution system falls onto the first of many layers of fill. The function of fill, which occupies much of the interior of a cooling tower, is to speed up the dissipation of heat from the water by increasing the amount and duration of contact between the water and the air in the tower. Fill accomplishes this objective by promoting the formation of droplets and water film and by increasing the wetted surface in contact with air. At the same time it should provide low resistance to the flow of air and should maintain a uniform distribution of water and air.

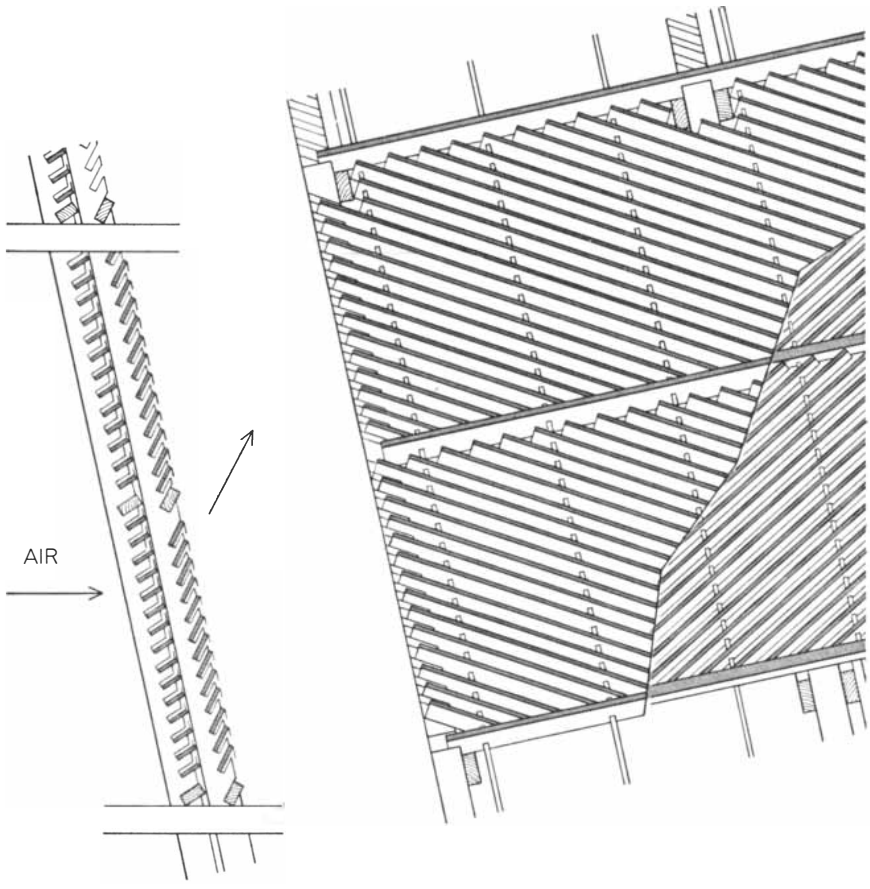
In most industrial towers fill is of the splash type, meaning that it consists of small bars or planking set horizontally [*see top illustration on preceding page*]. Water splashes downward from one level of bars to the next. Good exposure of water surfaces to the passing air is thus achieved because the water is constantly broken up into fine droplets and films by splashing as it falls.

Wood is the usual material for splash fill, although in recent years strips of perforated plastic have been developed for the purpose. Redwood has long been popular; lately fir has gained in use as a result of improvements that have been made in wood preservatives. Occasionally one finds metal or ceramic splash bars, but they are costly and so tend to be installed only in special applications.

In a tower with splash fill it is important for the splash bars to be maintained in a horizontal position. If they sag, water will tend to flow through the tower in channels and the cooling capacity of the tower will be reduced. It is also important for the tower to be kept level; otherwise water will run to the lower ends of splash bars and channeling will again result.

Another type of fill that is gaining acceptance for smaller towers is called film fill because it tends to spread the falling water into a thin film flowing over a large total surface area. Film fill is made of plastic, metal or asbestos and is formed into complex shapes such as honeycombs. It is more expensive than splash fill, but it provides more efficient cooling within a given amount of space. On the other hand, film fill is more sensitive than splash fill to irregularities in the flow of air and the distribution of water, so that the tower needs to be designed to ensure that such irregularities do not arise. The fill must be uniformly spaced and well supported.

At the end of its passage through the tower the cooled water falls into a collecting basin at the bottom of the tower. From there it is pumped back to the place where it picked up heat—for example a steam condenser in a generating station—and begins another cycle.



DRIFT ELIMINATOR is depicted from an end (*left*) and the exhaust side (*right*). The configuration forces outgoing air to make two abrupt turns; the resulting centrifugal force separates water droplets from the air so that moisture downwind of the tower is reduced.

In addition to the fan and its motor, both of which have to be capable of long operation under rugged conditions, several other parts of a mechanical-draft tower have a bearing on the movement of air through the tower. The characteristic flared stack enclosing the fan on each cell of a tower performs several functions. It acts as a fan guard and as a means of conveying water vapor and air away from the tower. The stack also plays a role in the efficiency of the fan: the closer it can be built to the tips of the fan blades, the higher will be the efficiency of the fan (and the lower the noise of the fan's operation).

The louvers on the sides of the tower where air is admitted have the obvious function of bringing the air in efficiently and the less obvious function of preventing the loss of water. The louvers must admit air in such a way that it is distributed uniformly and undergoes a minimum drop in pressure. To prevent the

COOLING SYSTEM	CONDENSER AND AUXILIARIES		COOLING TOWERS AND BASIN		PUMPS AND CONDUITS		MAKEUP SYSTEM		COOLING LAKE		TOTAL INVESTMENT	
OCEAN	1.6	2.4	–	–	3.3	4.8	–	–	–	–	4.9	7.2
RIVER	1.7	2.6	–	–	3.3	4.8	–	–	–	–	5	7.4
LAKE	1.5	2.3	–	–	2.7	3.9	–	–	2.6	3.4	6.8	9.6
MECHANICAL-DRAFT WET TOWER	1.9	2.8	1.7	2.6	1.6	2.4	1.2	1.6	–	–	6.4	9.4
NATURAL-DRAFT WET TOWER	1.9	2.8	4.2	7.1	1.7	2.5	1.2	1.6	–	–	9	14
MECHANICAL-DRAFT DRY TOWER	1.1	1.7	12.2	19.3	2.1	3.4	–	–	–	–	15.4	24.4
NATURAL-DRAFT DRY TOWER	1.1	1.7	28	45	2.1	3.4	–	–	–	–	31.2	50.1

COST OF COOLING SYSTEMS is compared for 800,000-kilowatt power stations burning fossil fuel (*black*) and nuclear fuel (*color*). The figures represent millions of dollars at 1970 prices. In a dry tower the warm water circulates in pipes that are exposed to air.

loss of water they must be designed with the proper width, spacing and slope. In crossflow towers that operate under winter conditions the louvers are often placed so that they slope back under the fill. If the fan is on, the falling water washes the louvers and so alleviates icing. If the fan is off, the louvers are bathed in warm water and ice usually does not form.

The problem of drift—the loss of water with the air leaving the tower—is dealt with by eliminators installed in the airstream to the fans. They are built in intricate geometric patterns that cause the rising air to shift direction abruptly at least once. The centrifugal force that results from the shift separates the drops of water from the air, depositing them on the surface of the eliminator, where they accumulate and eventually flow back into the tower. A secondary function of the eliminator is equalizing airflow through the fill. The eliminator offers resistance to the flow, thereby producing a uniform pressure in the space between the eliminator and the fan. This equalization of pressure tends to provide a uniform flow of air through the fill.

An efficient eliminator must decrease drift by an acceptable amount without unduly resisting the air. Too much resistance would necessitate higher horsepower for the fan. The eliminator must also be able to collect the drift water and return it to the tower basin without reintroducing it into the stream of air being discharged from the tower. Finally, the eliminator functions in an environment that is both corrosive and erosive, and so it must be made of such materials as treated wood, galvanized or stainless steel, plastic and asbestos.

To support all these structural elements, withstand moving water and air without deterioration and provide stiffness against wind a cooling tower needs a substantial framework. The design of a frame must be worked out with care, taking into account not only engineering factors but also thermal, aerodynamic and economic ones. Usually frames are built of wood, with redwood favored because of its natural resistance to decay. In recent years treated fir has also been extensively used. Occasionally a frame is made of galvanized steel.

In operating a wet cooling tower one must pay close attention to the condition of the water. The *p*H must be controlled; intermittent chlorination is necessary to control microorganisms, and corrosive substances must be removed. The problem of discharging blowdown water into a natural body of water can be alleviated by treatment and in some situations by using blowdown water to supply other plant processes.

An example of an installation with large amounts of heat to carry off is an 800,000-kilowatt steam-electric generating plant. If the plant is a modern fossil-fuel-burning one, the amount of heat rejected to the condenser from the turbine exhaust steam is about 50 percent of the heat input to the boiler. This is equivalent to about 1.33 kilowatts of heat rejected for each kilowatt of electric power generated. For a plant of similar size operating on nuclear fuel about 66 percent of the heat input to the boiler is rejected to the condenser; this is equivalent to about two kilowatts of heat for each kilowatt of net generation.

Five options are available for cooling the steam condenser. The plant can use a once-through cooling water system or any of the four main types of cooling tower: wet (mechanical draft or natural draft) or dry (mechanical draft or natural draft). The total investment in a cooling system for an 800,000-kilowatt plant will range from about $4.9 million for a fossil-fueled plant with a once-through system using seawater to $50.1 million for a nuclear plant with a natural-draft dry tower [*see illustration above*]. These figures, which cover the condenser and its auxiliaries, the pumps and conduits and a cooling tower if there is one, are based on 1970 prices and include 16 percent for direct overhead costs. In general the capital costs of a given type of cooling system are about 50 percent higher for a nuclear plant than for one using fossil fuel. Natural-draft towers cost more than mechanical-draft towers and dry towers more than wet ones. Since investment costs are rising, the impact of fixed charges will increase the cost handicap against natural-draft towers and dry towers.

Comparing partial production costs, which include capital and fuel but not such items as labor and maintenance, one finds that there is not much difference between a once-through system and a wet cooling tower. With a wet cooling tower the partial production

costs would be increased between 3 and 10 percent, which represents an additional .1 to .2 mill per kilowatt-hour. A more significant difference appears in a comparison of partial production costs between a once-through system and a dry cooling tower. Here the partial production costs would be increased between 30 and 75 percent, corresponding to an additional one mill to 1.5 mills per kilowatt-hour.

Currently under discussion is the use of saltwater cooling towers for large generating stations along seacoasts. (The few saltwater towers in existence serve relatively small plants.) The first question to be decided in the public interest is whether or not any additional coastal water should be used for cooling. According to tower manufacturers, it would be technologically feasible to operate a saltwater tower at a large generating station. The investment cost of such a tower would be about 25 percent higher than the cost of a freshwater tower, primarily because of the need for more expensive materials and for high-performance drift eliminators. Maintenance and energy costs for such a system would also be higher because of the problems involved in working with salt water.

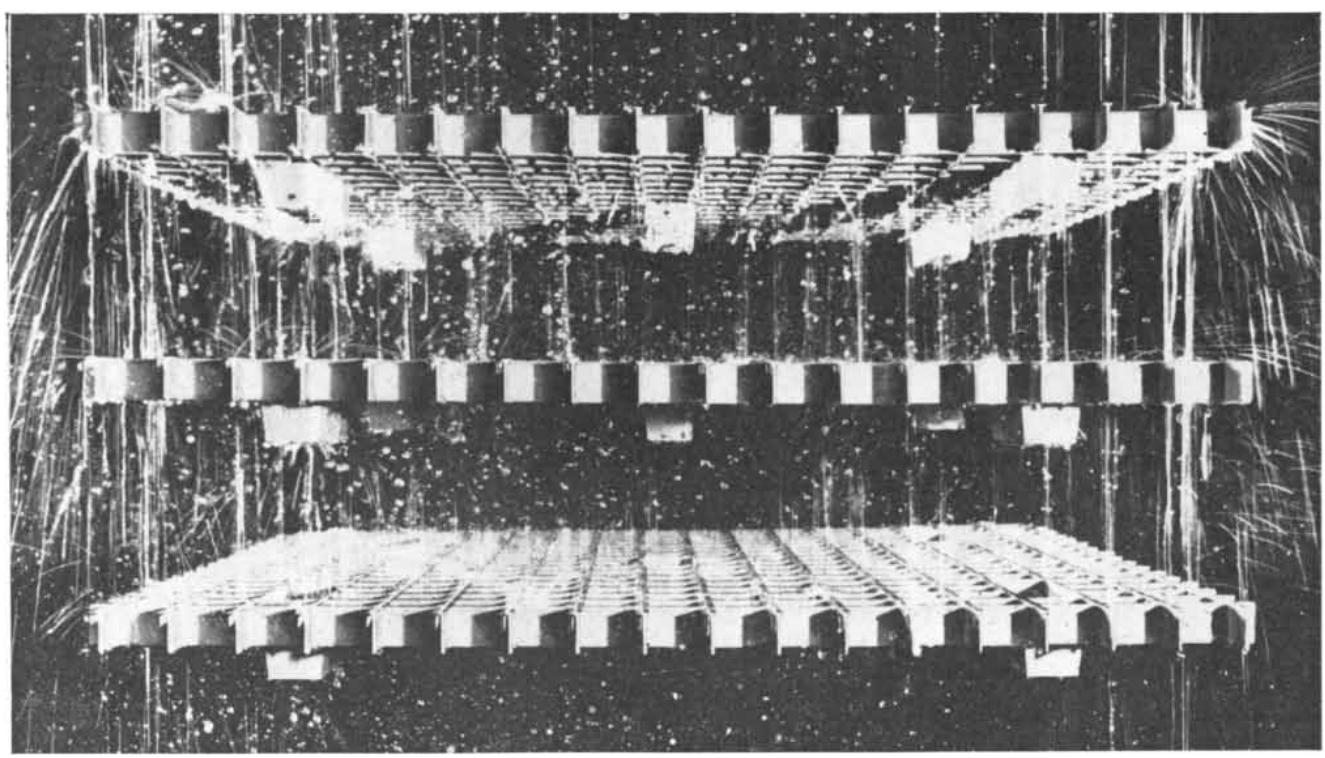
The conversion of existing once-through systems to cooling-tower systems may be needed in special cases but probably will not be done widely. For full conversion the capital cost at an 800,000-kilowatt plant would be about $3 million. Alternatively the conversion might involve only the supplemental use of a tower at certain times during the year to keep the temperature of discharge water below a given level.

The increasing size of large generating units will require larger wet cooling towers, which are already being designed. From the typical large mechanical-draft wet tower now in use—a multiple-cell unit about 55 feet wide at the base, 75 feet wide at the top and 325 feet long, with 28-foot fans powered by 200-horsepower motors—one can expect a progression to fans of larger diameter, with tower dimensions increasing proportionately. Present towers are adequate for cooling up to 400,000 kilowatts per continuous tower unit at a fossil-fueled plant; two tower units of seven cells or more each would be needed to serve an 800,000-kilowatt generating unit. The mechanical-draft wet tower of the near future will probably be capable of serving a million-kilowatt fossil-fueled plant with a single tower structure, although the economics and environmental characteristics of such a tower have not yet been established.

This typical large generating unit could also be served by a single natural-draft wet cooling tower about 410 feet in diameter at the base by 370 feet in height. Natural-draft wet towers now available can handle a nuclear unit as large as 1.1 million kilowatts, which is equivalent in cooling requirements to a fossil-fueled plant of about 1.65 million kilowatts. The present maximum size of natural-draft wet towers—about 600 feet in diameter and 500 feet high—is not expected to increase appreciably in the near future.

As for dry towers, the configuration for application to generating stations is not expected to change much from what is already used extensively in such industrial operations as large petrochemical plants. One standard module now produced is 60 feet long, 150 feet wide and has four 28-foot fans. The fan size is expected to increase, as in wet towers, but the module size will probably stay about the same.

The use of cooling towers in the water systems that cool the condensers in generating plants can be expected in an increasing proportion of new generating plants located inland. The number of towers operating with seawater may also rise. Most of the new towers will be of the mechanical-draft wet type, because that is the most economical type for nearly all applications.



BREAKUP OF WATER by fill is shown in this special arrangement of film fill. The falling water repeatedly hits pieces of fill and breaks up into small drops and films. In this way the water presents a large surface area to the air that is being moved through the tower. Cooling takes place mainly through the evaporation of a small part of the water that is circulated through the system.

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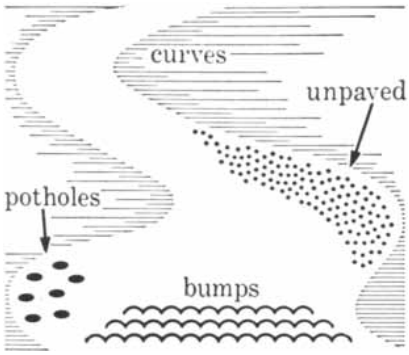

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This antecedent of the modern transformer served for nearly a century as the principal source of high-voltage electric current. It figured prominently in three epochal discoveries

by George Shiers

The discovery that "magnetism could produce electricity" was made independently by Michael Faraday in England in 1831 and by Joseph Henry in the U.S. at about the same time. Both men demonstrated in a variety of ways that an electric current is induced in a conductor when the conductor and a magnetic field are in motion with respect to each other. Their discovery of electromagnetic induction became a cornerstone of electrical science and technology. The first electric machines to be built (solely for laboratory use) were magnetoelectric generators. By the mid-1830's the electric telegraph, with magnets and coils, was in an early stage of development. A third device, the induction coil, reached a fairly mature form in just two years, between 1836 and 1838. Much of the pioneer work on this half-forgotten device was done independently by a physician in the U.S. and a priest in Ireland. Ultimately the induction coil played a central role in three epoch-making discoveries: radio waves, X rays and the electron, the first known subatomic particle. Moreover, it gave rise to the modern electric transformer, and before the advent of electronic devices it was the principal source of high-voltage electric current. Induction coils are still used by the millions to fire the spark plugs in automobiles.

In its simplest form an induction coil consists of an iron bar wrapped with two insulated windings: a few turns of heavy wire to carry the primary current and many more turns of fine wire to carry the induced current. When the primary circuit is broken, the collapsing magnetic field induces a brief current of high voltage in the secondary winding. An induction coil of this basic form was devised in 1836 by Nicholas J. Callan, a priest turned physics teacher at Maynooth College in County Kildare, near Dublin. In order to study the induction of the secondary currents described by Faraday he built a coil consisting of a horseshoe bar of iron wound with 50 feet of thick copper wire and 1,300 feet of thin iron wire. The source of current was a small battery. To interrupt the primary circuit Callan employed a hand-cranked contact breaker. It is surprising that Faraday, a genius at devising simple but elegant ways of studying electricity, did not himself think to build such a device.

A description of Callan's experiments appeared early in 1837 in a new monthly technical journal published in London titled *The Annals of Electricity*. Callan then built "the most powerful electromagnet yet constructed," as he described it a few months later in the same journal. His new induction coil consisted of an iron bar more than two inches thick and 13 feet long bent into a horseshoe wrapped with two insulated coils about 10 times longer than the first ones. When Callan rapidly interrupted the primary circuit with his contact breaker, he induced a current large enough to create a miniature arc light between charcoal rods attached to the ends of the secondary winding. He estimated the strength of the induced current by the shocks to himself, and he is said to have electrocuted a fowl with the intense secondary currents.

The publisher of *The Annals of Electricity* was William Sturgeon, an electrical experimenter and lecturer, who in 1825 devised the first electromagnet with a soft-iron core. A self-taught and inventive man, Sturgeon improved on Callan's design by constructing the two windings in the form of a double-wire helix mounted on a wood bobbin. He also introduced new kinds of hand-cranked primary interrupters; one employed a movable wire that dipped into a cup of mercury and the other a notched disk with a jumping contact wire to provide more rapid breaks.

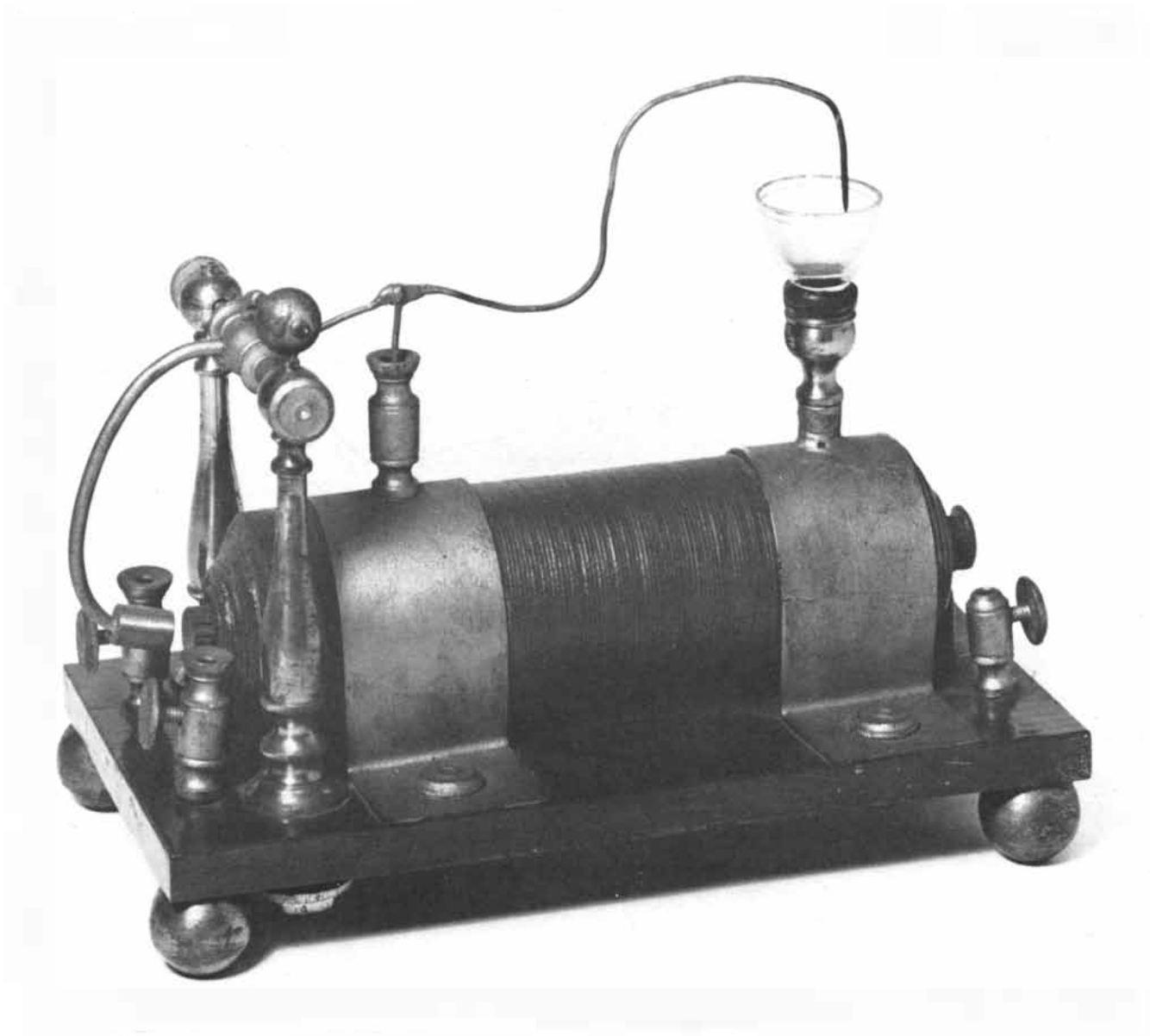
In trying out the coil Sturgeon found that more intense shocks were felt when a core of solid iron was inserted in the bobbin. He then found that a core consisting of fine iron wires made a better core than a solid piece of iron when the primary circuit was interrupted at a high rate. The superiority of iron wires over solid iron for the core appears to have been observed at about the same time by a colleague at the Polytechnic Institution of London, George H. Bachhoffner.

The historical record is not clear, but it is likely that Sturgeon was responsible for an important innovation demonstrated at a lecture at the Manchester Mechanics' Institute and mentioned in his journal of October, 1837. The innovation consisted in wrapping the primary and secondary coils on separate bobbins so that by sliding the primary coil into the secondary coil one could alter the secondary voltage smoothly over a considerable range. Induction coils of this type, known as two-circuit air-core tuning inductances, or "loose couplers," were widely employed in radio receivers up to 1920.

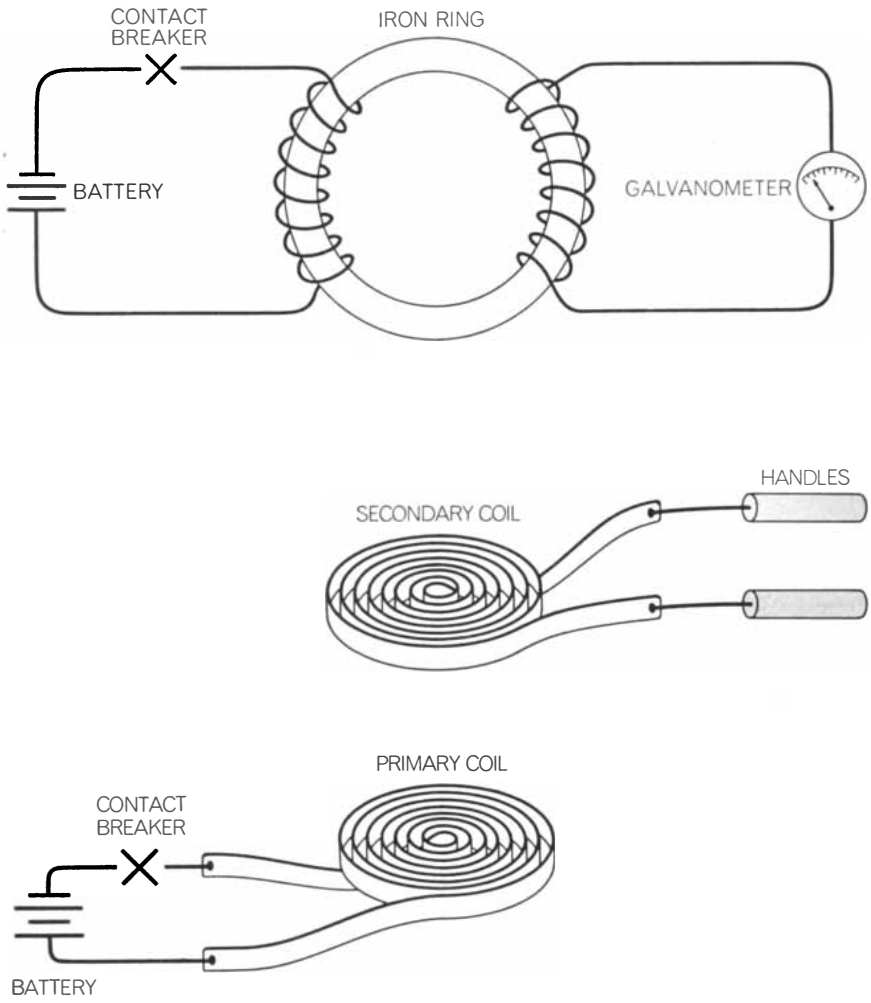
The induction coil was quickly perceived as being a convenient means of obtaining high voltages, either for laboratory experiments or for hypothetical therapeutic purposes. (The effects of an electric shock on the human body had been studied ever since the introduction of the Leyden jar in 1745.) Before the advent of the induction coil there had been only two ways of obtaining an electric current of high voltage: one was to use bulky and expensive primary batteries; the other was to turn the crank of a friction machine in which conductive leather pads rubbed on the surface of a rotating glass cylinder or plate.

The enthusiasm that Callan, Sturgeon and others exhibited for electromagnetic induction was matched by Charles Grafton Page, a physician of Salem, Mass., whose interest in electrical experiments began soon after his graduation from Harvard College in 1832 and continued until his death in 1868. Stimulated by Henry's work on induction, Page in 1835 designed a coil consisting of a single spiral strip of copper without a secondary winding. In this respect it resembled some of Henry's coils. Page, however, attached extra terminals at intervals between the ends [*see bottom illustration on next page*]. When he interrupted the flow of current through the spiral, he found that shocks could be felt by touching any pair of terminals. Page's autoinduction coil appears to be the first autotransformer, that is, a transformer with a single winding. An account of his experiment was published in *The American Journal of Science and Arts* in October, 1836, and in Sturgeon's *Annals*. The American journal was established in 1818 by Benjamin Silliman, a lawyer who became better known as a chemist, geologist and scientific publisher.

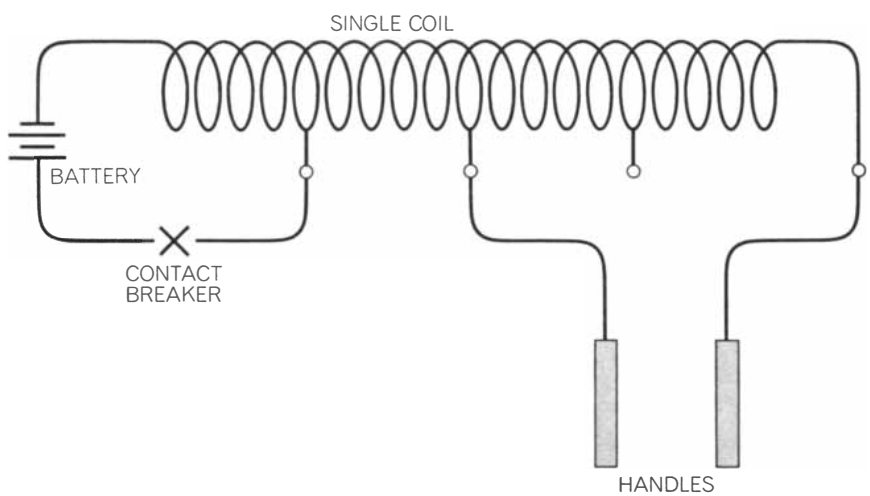
Page went on to make a larger autoinduction coil and also devised various types of automatic contact breakers. One of these consisted of a copper star wheel mounted within the poles of a horseshoe magnet. Points on the wheel dipped into a cup of mercury, thus allowing current to pass through the wheel. The current reacted with the magnetic field and caused the wheel to rotate continuously. In an entirely different design Page set up a tiny electromagnet with two separate windings, pivoted in the center like a beam. The ends of the windings dipped into mercury cups, and a horse-



EARLY INDUCTION COIL, designed in 1838 by Charles Grafton Page, a physician of Salem, Mass., was in most respects a prototype of later devices. The primary and secondary windings of insulated copper wire were supported on a wood bobbin containing a core of soft-iron wires. The circuit from a battery (*not shown*) to the primary coil was equipped with an automatic interrupter. When the core was magnetized, it attracted the iron hammer at lower left, which raised the bent wire at top, breaking the primary circuit in the mercury-filled glass cup at upper right. (The contact in the smaller mercury-filled cup at upper left was permanent because of the comparatively small motion of its contact arm.) The hammer was then released, the wire again made contact by dipping into the mercury and the cycle was automatically repeated. The device was photographed at the Smithsonian Institution.



ELECTROMAGNETIC INDUCTION was discovered independently in the early 1830's by Michael Faraday in England and Joseph Henry in the U.S., using the experimental devices depicted schematically in these two drawings. In the case of Faraday's ring (*top*) the needle of the galvanometer is momentarily deflected one way when the primary circuit is made and the other way when the circuit is broken. In the case of Henry's spiral coils (*bottom*) a shock is obtained from the handles whenever the primary circuit is made or broken.



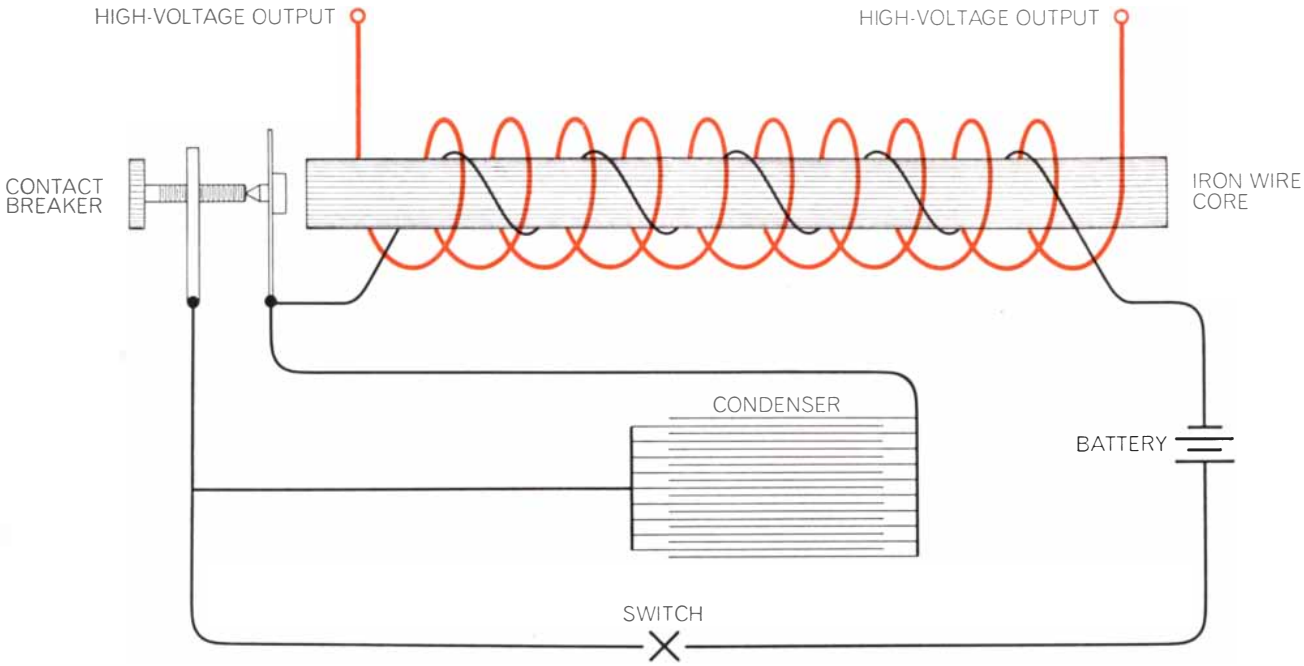
FIRST AUTOTRANSFORMER, invented by Page in 1835, resembled some of Henry's autoinduction coils in that it consisted of a single spiral strip of copper without a secondary winding. Page, however, attached extra terminals between the ends. When the flow of current through the spiral was interrupted, shocks could be felt by touching any pair of terminals.

shoe magnet was positioned near one end to produce a rocking motion. Reversals of current in the magnet coils kept the beam in motion and also interrupted the primary circuit to the induction coil.

Before the end of 1838 Page had designed a new type of double-wound coil [*see illustration on preceding page*]. Unlike many other examples of technical evolution, where the preferred form is quite different from early models, this coil was in most respects a prototype for later commercial devices. The windings of insulated copper wire were supported on a wood bobbin containing a core of soft-iron wires. The most noteworthy feature is the automatic hammer break that operates a mercury interrupter. A layer of oil on the surface of the mercury served to reduce oxidation, quench the spark and thereby increase the rapidity of the break. Page's coils were made by Daniel Davis, an instrument maker in Boston. Davis later made and sold these coils as a commercial product; he also built magneto machines invented by Page.

A variety of designs and relatively minor improvements in coil construction, contact breakers and general assembly appeared during the 1840's. Throughout that decade coils were made in increasing numbers. Academies with programs in natural philosophy bought them, ostensibly for demonstrating basic principles but probably more for the startling and showy results (judging from contemporary textbooks) than for truly scientific uses. Coils were also eagerly sought by those who wished to explore or exploit the "revitalizing" effects of severe electric shocks on themselves or their patients [*see top illustration on page 84*].

The final phase of the coil's development was reached during the 1850's. Heinrich Daniel Ruhmkorff, a German instrument maker living in Paris, turned his attention in 1851 to the construction of better and more powerful coils. Ruhmkorff used glass as a liner between the primary coil and the secondary coil and also for end plates to support the windings and for pillars to carry the high-potential secondary leads. He increased the number of turns on the secondary winding, added insulation between the layers, took great care in the assembly and thereby produced coils that could deliver sparks two or three inches long. The quality of his products quickly brought him fame, and such coils soon became known as Ruhmkorff coils. In 1864 Ruhmkorff was awarded a prize of some $10,000 established by



TYPICAL INDUCTION COIL is shown in this schematic diagram. The contact breaker automatically interrupts the current from the battery in the primary coil (*black*). The resulting rise and fall of the magnetic field induces a voltage in the secondary coil (*color*). Because the secondary coil has many more turns than the primary coil, a high voltage difference can be built up between the output terminals. The capacitor in shunt with the contact breaker (an innovation suggested in 1853 by the French physicist Armand Fizeau) almost eliminates sparking, reduces contact wear, prevents sticking of the contacts by fusion and increases the secondary voltage.

Napoleon III for the most significant application of electrical science.

In spite of the improvements introduced by Ruhmkorff a serious problem still remained: how to reduce the fierce sparking between the vibrator contacts (like those in an electric bell) that quickly caused deterioration of the contact surfaces. A solution was found in 1853 when Armand Fizeau (who four years earlier had successfully measured the speed of light with a system of mirrors) suggested that a condenser, or capacitor, be connected across the breaker contacts. Three years later Fizeau's colleague Jean Foucault (who had demonstrated the rotation of the earth by means of a pendulum) proposed an improved form of mercury interrupter [*see bottom illustration on next page*].

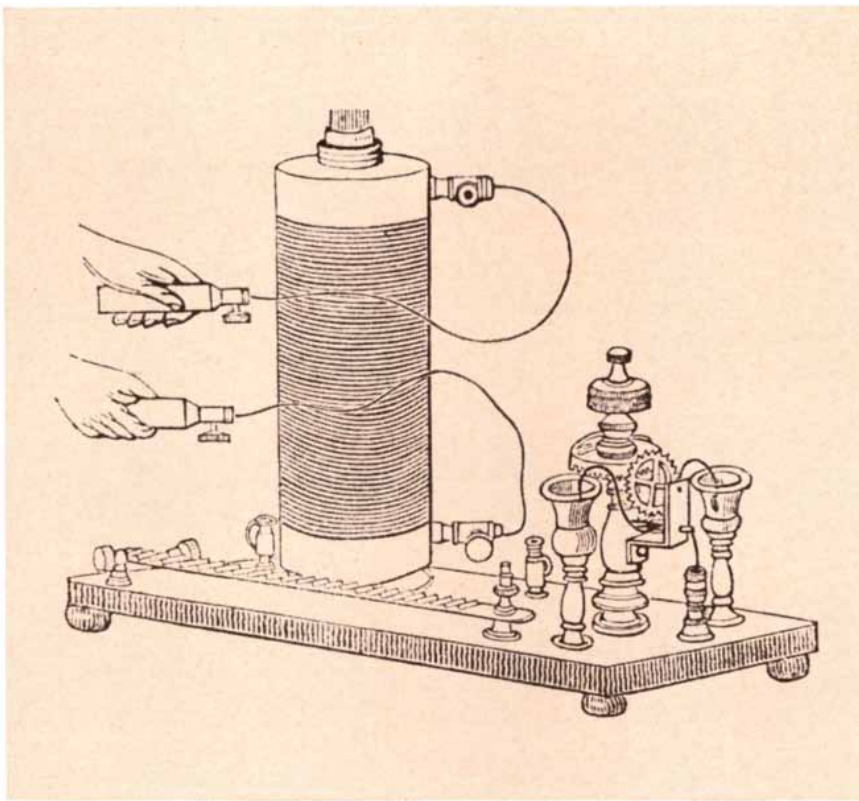
The condenser was made of sheets of tinfoil interleaved with insulating layers of oiled silk. (Later the insulating layers were waxed or varnished paper, guttapercha or mica.) The assembly was compressed, bound tightly and installed in a hollow section of the baseboard that supported the coil. By absorbing the high voltage induced in the primary coil as the circuit is broken, such a capacitive shunt almost eliminates the sparking at the breaker contacts, reduces contact wear, prevents sticking of the contacts by fusion and increases the secondary voltage by making possible more rapid change of the magnetic state of the core.

This important technical contribution and other practical innovations came at about the same time. As larger coils with a secondary winding consisting of five miles or more of wire were built, longer and more spectacular sparks were obtained. The increased voltage, however, set up stresses within the secondary winding that frequently resulted in destruction of the coil. This limitation was overcome by dividing the secondary coil and winding it in sections with vulcanite or glass separators between them. The idea of dividing the secondary coil was proposed in 1852 by Charles and Edward Bright, who were well-known engineers of the time. Other improvements in wire insulation, construction methods and automatic contact breakers were made by (or reinvented by) numerous workers during those years.

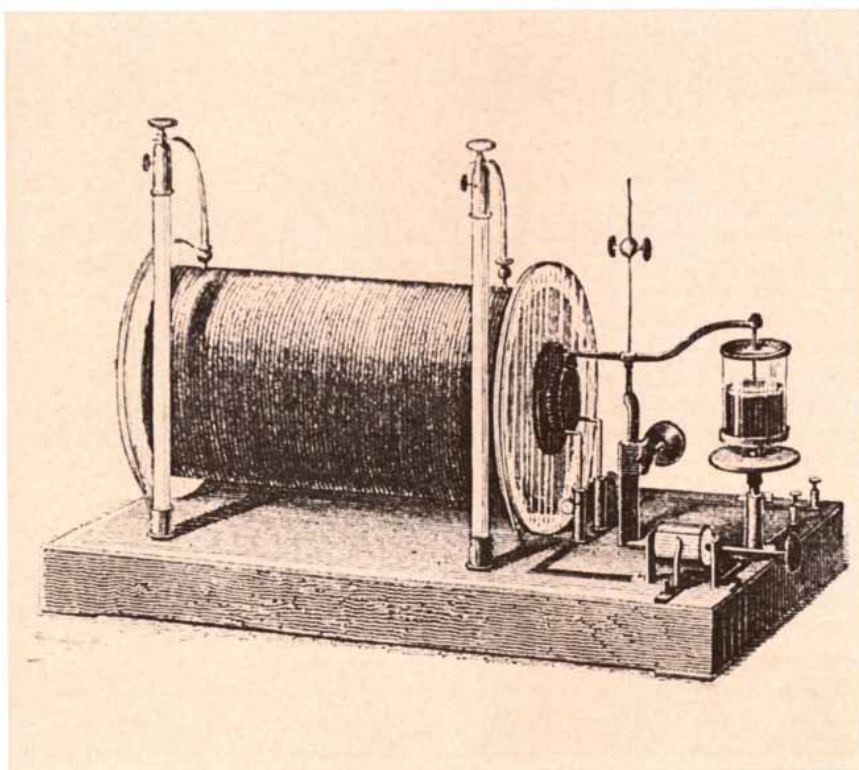
By 1860 the inductorium, as the induction coil was often called, had reached a mature stage of development. From this time on it became a common instrument to be found in almost any school, college or scientific laboratory. In the standard demonstration the coil was used to create a series of noisy sparks several inches long between electrodes in air. Lecturers would often add to this demonstration a spectacular shower of sparks created by releasing the discharge among spangles of tinfoil pasted inside a glass tube. Other favorite experiments included melting fine iron wire, burning wood along a track in which nitric acid served as a conductor, setting fire to paper, igniting a pinch of gunpowder or exhibiting the glow discharge within an evacuated tube or globe [*see top illustration on page 85*].

Many physicians thought it fashionable, and no doubt profitable, to use the induction coil as a source of "Faradic currents" for the supposed relief of miscellaneous ailments. The strength of the shock was controlled in sundry ways: by a sliding primary coil, by a sliding core, by a removable copper cylinder that served as an inductive shield over the core or by adjustment of the vibrator contacts. These medical coils were furnished with different styles of electrodes to complete the electric circuit through the human body. Showmen and itinerant lecturers quickly learned that audiences enjoyed seeing the effect of shocks administered to volunteers, of whom there was never a lack. Later in the century an induction coil housed in a fancy box with metal handles, a regulator and a coin slot became a familiar attraction in penny arcades.

As with other kinds of energy converter, the demand continued for bigger, better and more powerful coils. Beginning in the late 1850's larger coils, often



HAND-OPERATED MERCURY INTERRUPTER (*right*) was employed with this vertical induction coil, typical of many built around 1850 for scientific and "medicinal" purposes.



RUHMKORFF COIL, developed during the 1850's by Heinrich Daniel Ruhmkorff, a German instrument maker living in Paris, incorporated many improvements over earlier designs. Glass was used as a liner between the primary coil and the secondary coil and also for end plates to support the windings and for pillars to carry the high-potential secondary leads. The particular coil shown in this engraving is equipped with an improved form of mercury interrupter devised by Jean Foucault of France. Base contains a parallel-plate condenser.

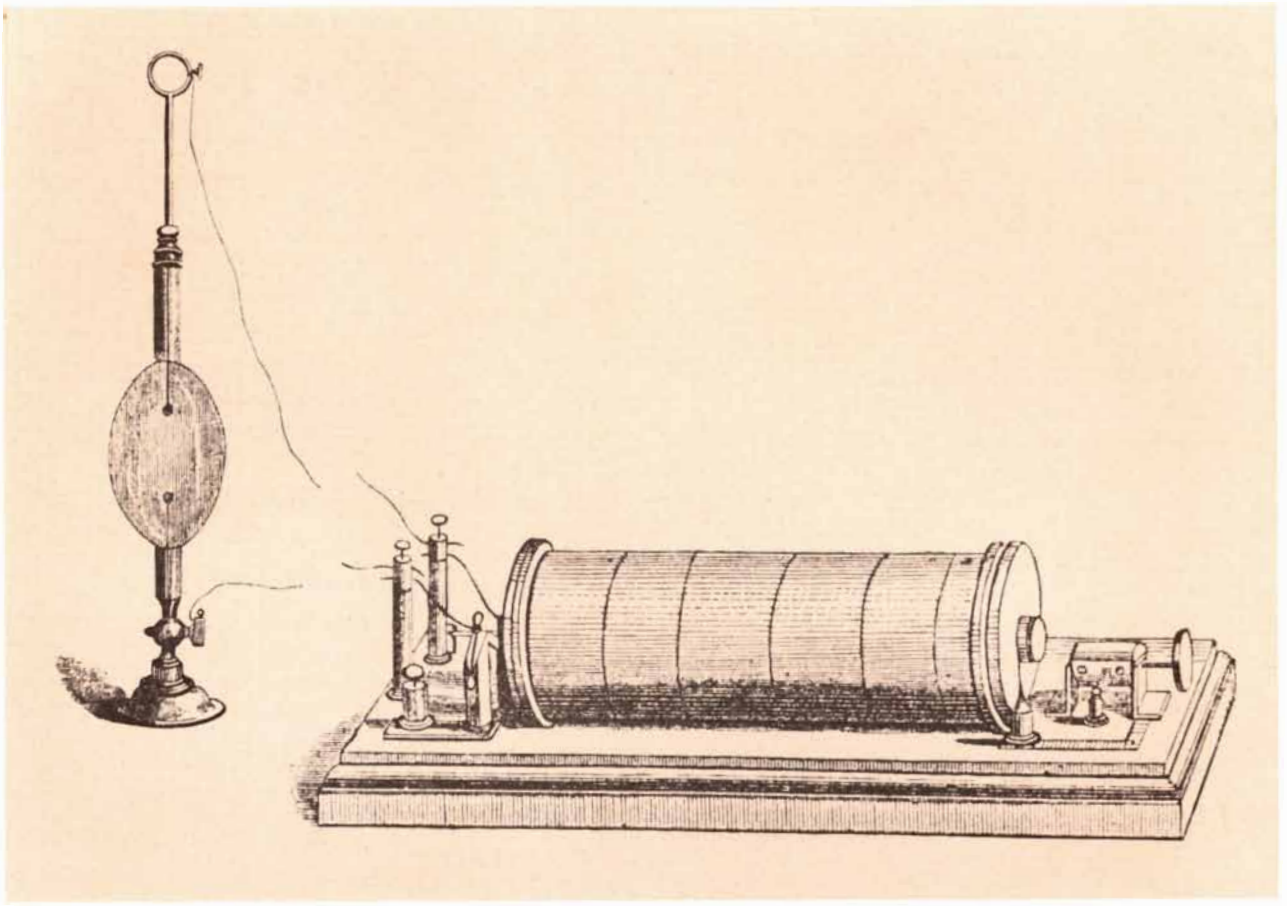
following Ruhmkorff's design, were built by many instrument makers. Some of the most successful were constructed by J. N. Hearder of Plymouth in England and by E. S. Ritchie of Boston. The length of the spark grew to 10 or 12 inches. Callan designed a coil capable of giving 15-inch sparks, but he died before it was completed. In 1869 a London instrument maker, A. Apps, built a coil that could deliver a spark of 30 inches; it was the center of attraction during demonstrations at the London Polytechnic.

Several years later William Spottiswoode, a London printer, mathematician and experimental physicist, gave Apps an order for the largest induction coil ever made. A description of this ambitious instrument was published in *The Philosophical Magazine* early in 1877 [*see bottom illustration on opposite page*]. The iron core is 44 inches long and the secondary coil consists of 280 miles of wire in more than a third of a million turns. This giant coil, capable of producing sparks up to 42 inches long between open electrodes, was used by Spottiswoode for spectroscopy and for studying gaseous discharges.

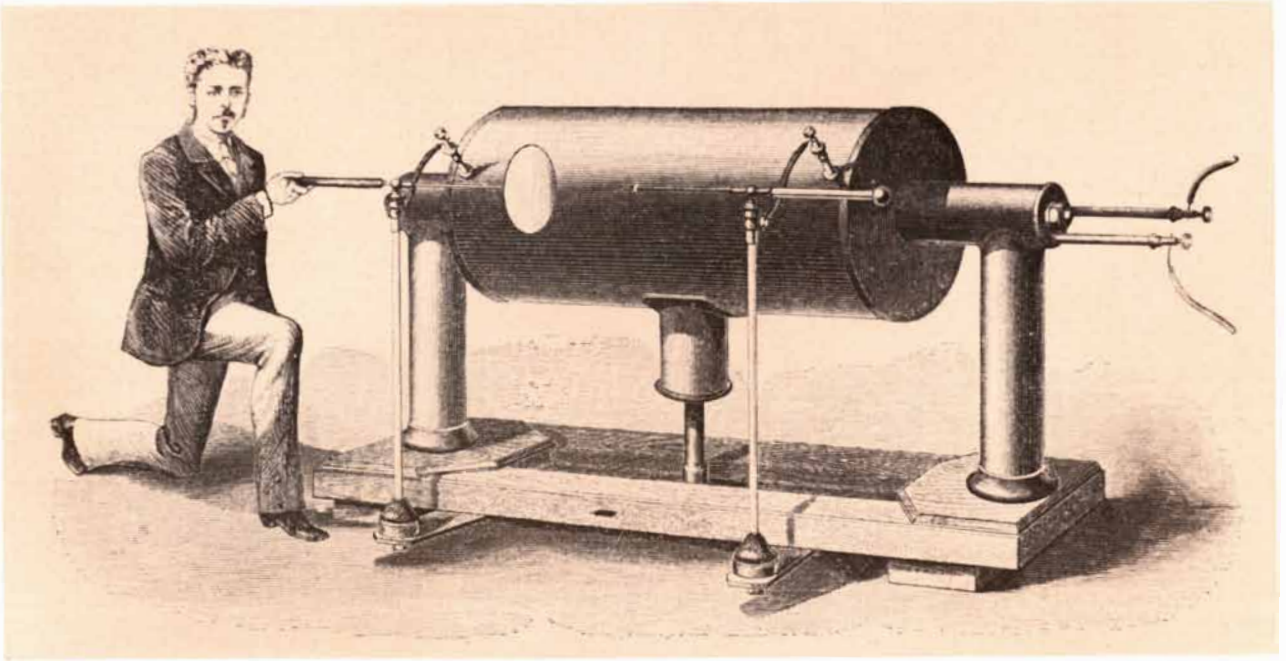
In contrast to these medical, frivolous and scientific uses, the induction coil was finding its way into engineering with the growing interest in electric power systems employing alternating currents. In 1867 William Grove used a magneto generator to excite an induction coil. This was a primitive alternator and step-up transformer system. Ten years earlier Cromwell Varley had patented a new coil design in which the iron core wires were bent around the outside of the windings to form a closed magnetic circuit. Familiar to early radio enthusiasts as a "hedgehog" coil (and a favorite for home construction), this closed-core design later developed into the basic power transformer.

By the end of the 1870's a number of inventors had put forward proposals for electrical lighting systems in which induction coils were assigned an important role. In some of the systems the coils were supposed to interrupt direct current and yield an alternating current of higher voltage. In others the coils were to act as transformers fed by alternating current. Although none of these proposals materialized into successful systems, the induction coil (without its breaker) grew into the power transformer. Meanwhile its little brother, in the form of a small voice-frequency transformer, appeared as an essential component in the telephone.

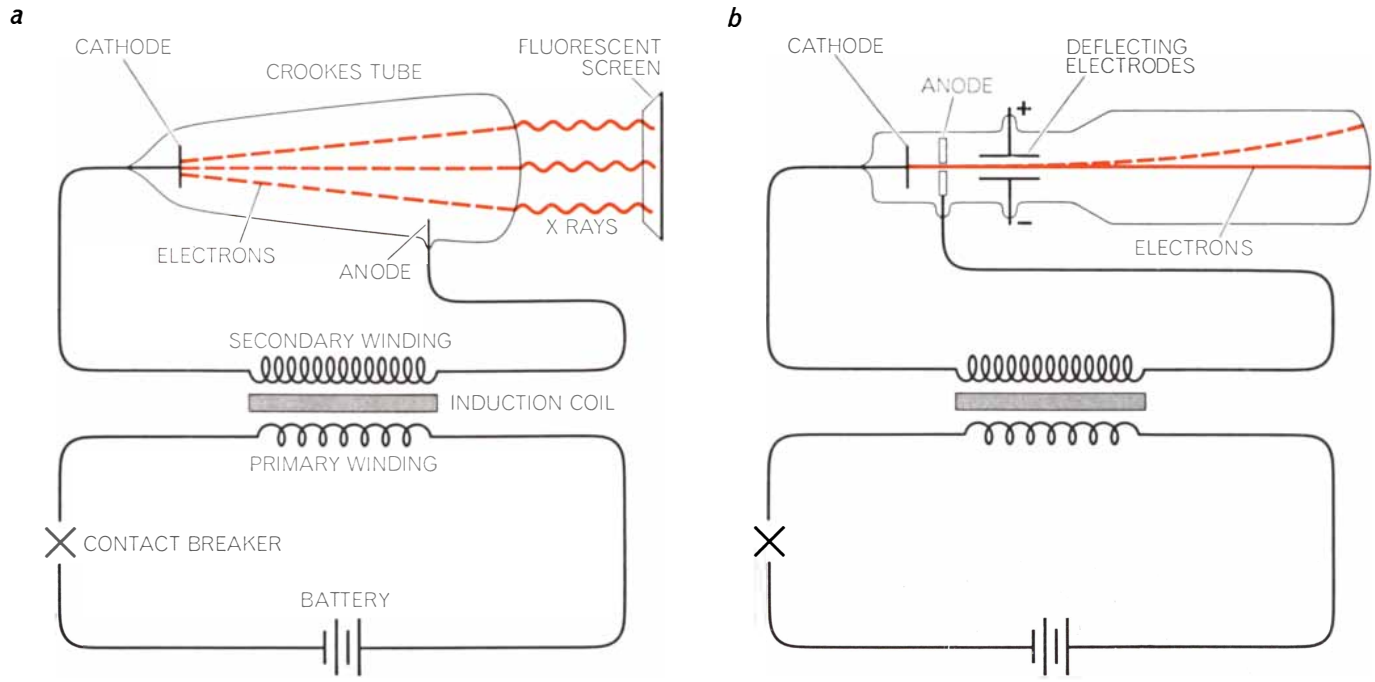
The availability of improved coils during the 1850's stimulated serious re-



"ELECTRIC EGG" (*left*), an evacuated glass chamber connected to an induction coil (*right*), was employed in the late 1850's to demonstrate glow discharge. Air was withdrawn from the globe by a hand-operated pump attached to the base support. The striking luminosity of the discharge made this a favorite demonstration in schools, colleges and scientific laboratories through the 1860's.



LARGEST INDUCTION COIL EVER MADE was built in 1876 by A. Apps, a London instrument maker, for William Spottiswoode, a London printer, mathematician and experimental physicist. The iron core of the device was 44 inches long and the secondary coil consisted of 280 miles of wire in more than a third of a million turns. The coil was capable of producing sparks up to 42 inches long between the open electrodes. It was used by Spottiswoode for spectroscopy and for studying gaseous discharges.



FOUR IMPORTANT DISCOVERIES involving the use of the induction coil were made near the close of the 19th century. Wilhelm Konrad Röntgen, while studying the discharge produced in a Crookes tube by means of a Ruhmkorff coil, noticed a glow from a nearby fluorescent screen and discovered X rays (*a*). J. J. Thomson, using an induction coil and special tubes equipped with extra electrodes, found that cathode rays could be deflected by a magnetic field, proving that they were negatively charged "corpuscles" (electrons) released by the atoms of the cathode (*b*). Heinrich Hertz demonstrated the transmission of electromagnetic waves through

search, particularly into the conduction of electricity through gases. The upsurge of interest in this line of inquiry, which eventually led to a revolution in physics, began with the studies of Faraday, Grove and John P. Gassiot in England and those of Julius Plücker and Johann Wilhelm Hittorf in Germany. In the middle of that decade Heinrich Geissler, a skilled instrument maker and glass-blower who worked with Plücker at the University of Bonn, developed glass tubes with sealed-in electrodes and an improved mercury vacuum pump. These advances enabled Geissler to build discharge tubes with a higher vacuum than any previously known. Early experimenters obtained the high voltages needed to operate discharge tubes by wiring large batteries in series and even by using old-fashioned friction machines. By the end of the decade, however, they had turned to the battery-powered induction coil. It was convenient, compact, portable, self-operating, easily controlled by a switch in the primary circuit and the voltage in its secondary circuit was readily adjustable.

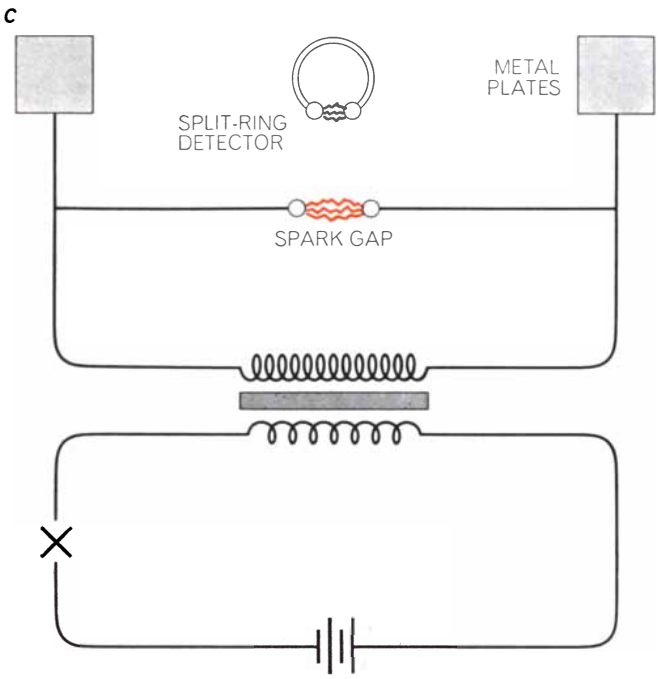
During the 1860's and 1870's the characteristics of ionized gases and cathode rays, as they were later known, were slowly revealed by Plücker, Hittorf and Eugen Goldstein in Germany and by Spottiswoode, his friend Warren de la Rue and William Crookes in England. In 1879 Crookes achieved international fame with a series of skillful demonstrations of the "ultragaseous state," or "radiant matter," as he called the phenomena of discharges at very low pressure.

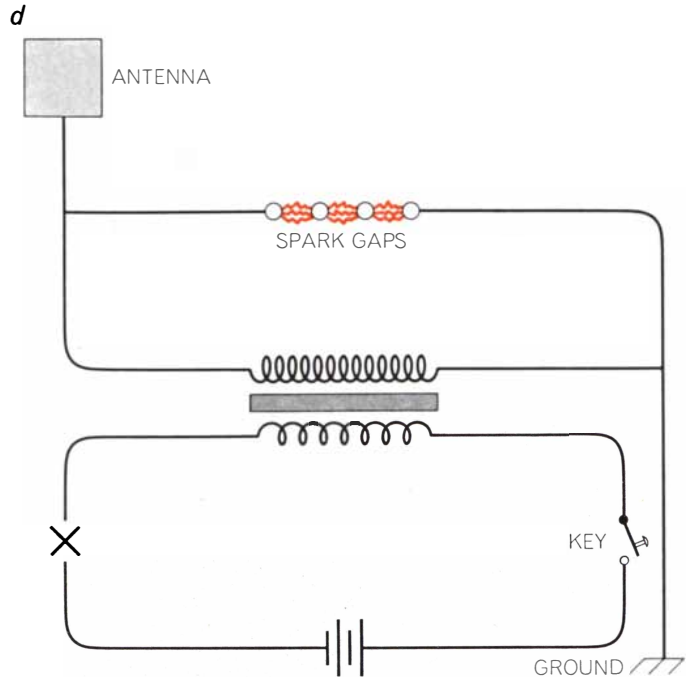
For the next 20 years, as investigators probed deeper into the nature of electricity, the induction coil and glass tubes containing rarefied air or a trace of added gas—variously known as Geissler, Hittorf or Crookes tubes—were constant companions. Now electricity was no longer confined to metallic or liquid conductors. It could be projected through an enclosed space relatively free of matter. Depending on the voltage, the size of the tube, the degree of the vacuum and the nature of the gas, it was possible to produce a solid glow throughout the tube, streamers of colored light, a striated discharge in the form of luminescent patches separated by dark spaces or brilliant fluorescence of the glass. Much was learned from these fascinating but baffling displays.

As the 19th century came to a close electrical ignition was added to internal-combustion engines. Either a magneto or a battery and spark coil with a timed contact breaker furnished the high voltage needed to ignite the gaseous fuel. Made in the tens of millions since those days, the ordinary automobile spark coil (which is still in service) is the commonest version of the induction coil. Concurrently with this practical application the knowledge gathered with the evacuated tube and the spark coil led to two revolutionary discoveries.

Toward the end of 1895 Wilhelm Konrad Röntgen was experimenting with a variety of tubes and a Ruhmkorff coil in his laboratory at the Physical Institute of the University of Würzburg. As he was studying the discharge from a Crookes tube in a darkened room he noticed a glow from a fluorescent screen lying on a nearby table, even though the tube was covered with black cardboard. This significant observation started Röntgen on a series of investigations that led to his announcement in December of the discovery of "a new kind of rays." Within a few weeks dozens of laboratories all over the world had duplicated Röntgen's simple apparatus and were studying the startling properties of the new and strange X rays.

The second great event occurred less than two years later at the University of Cambridge. J. J. Thomson, using an induction coil and special tubes set up in the Cavendish Laboratory, discovered that the cathode rays consisted of particles. As a result of these experiments Thomson advanced the bold hypothesis that the hitherto "indivisible" atom was





space with the aid of a "transmitter" consisting of zinc plates attached by wire to the spark gap of an induction coil and a "detector" consisting of a simple wire ring broken by a tiny spark gap (*c*); when the coil was discharged, a spark was observed in the detector several feet away. Guglielmo Marconi, using an induction-coil transmitter similar to Hertz's, demonstrated the feasibility of transmitting telegraph signals without wires when he joined one side of the spark gap of the coil to an antenna and connected the other side of the gap to a metal plate buried in the ground (*d*); signals were produced with telegraph key in the primary circuit of the coil.

actually made up of smaller particles. He suggested that atoms contained negatively charged "corpuscles" and holes, and that the corpuscles could be released to form cathode rays. His corpuscles, better known as electrons, soon became the key to a new era in physics and to a new technology.

Meanwhile a somewhat earlier discovery, pursued in large measure with the help of the induction coil, was leading to the invention of radio. In the two-year period 1886–1888 Heinrich Hertz, professor of physics at the Technische Hochschule in Karlsruhe, discovered and demonstrated the transmission of electromagnetic waves through space. Hertz noticed that a spark jumped between the leads of a single spiral coil when a Leyden jar was discharged several feet away. To pursue this observation he built a "transmitter" consisting of zinc spheres or plates attached by wire to the spark gap of an induction coil, which served as an oscillator. As a detector of the transmitted radiation Hertz used a simple wire ring broken by a tiny spark gap. By careful experiments with reflectors and wire prisms he proved the quasi-optical nature of electromagnetic waves.

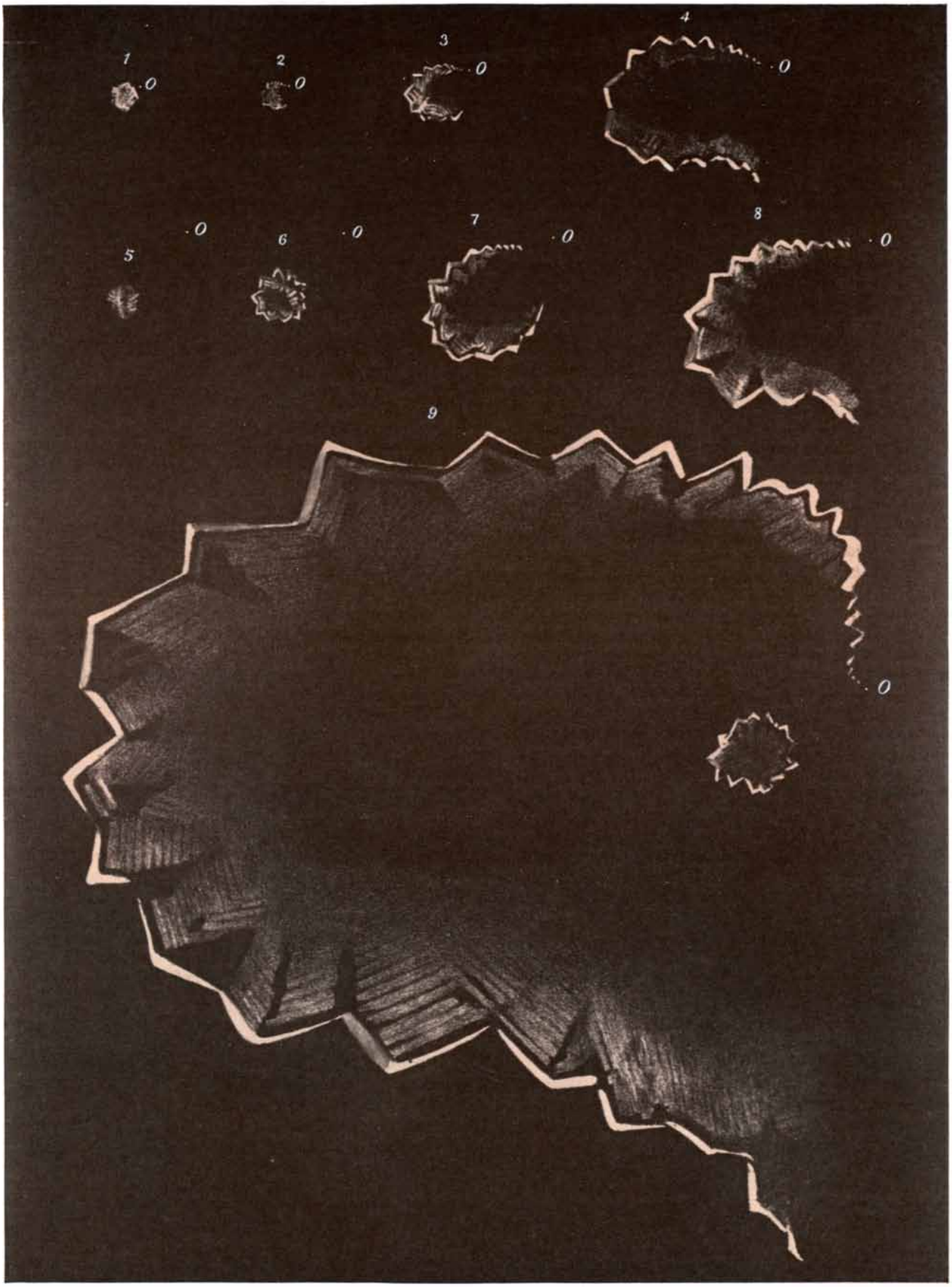
Rarely has the interval between the discovery of a phenomenon and practical application been so brief. In 1896 Guglielmo Marconi demonstrated the transmission of telegraph signals without wires, using an induction-coil transmitter. Marconi joined one side of the spark gap of the coil to a wire raised in the air (the antenna) and connected the other side of the gap to a metal plate buried in the ground. Signals were produced with a telegraph key in the primary circuit of the induction coil. When Marconi discovered that an increase in the height of the antenna extended the distance of transmission, he knew that wireless telegraphy was truly feasible.

Throughout the closing years of the century Marconi continued to cover greater distances over land and water. In these advances he used higher antennas and bigger coils to power the transmitter. Then, as the new century began, he set his mind on spanning the Atlantic with Hertzian waves. To ensure a chance of success in this bold enterprise, he had to replace the familiar induction coil with more powerful electric machinery.

A system employing an alternator with step-up transformers, banks of huge plate condensers, choke coils, double spark gaps and a multiwire antenna 160 feet high was set up near the coast of Cornwall in England. Marconi, stationed in Newfoundland, received weak signals from this transmitter in December, 1901. Within a few years long-distance transmission of telegraph messages by means of high-powered machinery became a commercial operation.

This was not the end of the ubiquitous induction coil. For a few years it served as the primary source of high electric potential for wireless apparatus in merchant ships and short-range land stations and for powering the increasing number of amateur transmitters. During World War I induction coils were manufactured by the thousands, particularly for low-power portable and mobile transmitters. After the war thousands of surplus induction coils were eagerly put to use by electrical enthusiasts.

By 1920, however, electron tubes and their circuits came to the forefront and quickly replaced other means of generating radio waves. High-frequency alternators, arc generators and other systems employing spark gaps were relegated to the scrap heap. Commercial alternating-current power, step-up transformers and vacuum-tube rectifiers furnished direct current at high potentials for X-ray equipment, radio transmitters and receivers and other devices used in science and industry. With silent electronic circuits doing the job more elegantly and precisely than a torrent of sparks, the induction coil became a fading memory of more primitive days.



FORTIFICATIONS drawn in 1870 by a British physician, Hubert Airy, show a characteristic form: bands of bright lines, approximately *C*-shaped, that expand across the visual field (*1–4 and 5–8*). In each case the white dot (*0*) is the point on which the subject's gaze was fixed. The large figure (*9*) shows the detailed form of the bands, which are made up of sets of sharply angled short lines.

The Fortification Illusions of Migraines

The visual displays that are seen before certain headaches provide information on the arrangement of nerve cells in the visual cortex of the brain. The evidence suggests that the pattern is hexagonal

by Whitman Richards

How does the brain perceive objects in the world outside it? In an effort to answer that question neurophysiologists have for the past 30 years or so been probing animal brains, recording their nerve impulses and thus determining how their neural elements respond to different kinds of stimuli. The resulting data are generally complex and difficult to interpret, with one outstanding exception: data collected from regions of the brain that receive information directly from the sense organs. In these primary receiving areas the data are often remarkably unequivocal; single neural elements are found that respond, in roughly an all or nothing fashion, only to highly specific kinds of stimuli, such as lines of a certain length and orientation [see "The Visual Cortex of the Brain," by David H. Hubel; SCIENTIFIC AMERICAN, November, 1963]. The behavior of single neurons in these areas is usually so stimulus-specific—so dependent on the nature and orientation of the feature that stimulates them—that such neurons are considered to be "feature detectors," and each neuron or neural unit is labeled according to the feature that triggers its activity. By identifying the features that trigger neurons at various levels in the sensory pathways one can begin to reconstruct the method the brain uses to analyze and process incoming information about the external world.

Whereas neurophysiologists have only recently obtained this direct evidence on the stimulus features to which different parts of the animal brain respond, indirect evidence on the abstracting operations performed by the brain has been available for many centuries. What is perhaps the most impressive indirect evidence on feature detectors comes from man's own experience when selected parts of his brain become spontaneously active. Such abnormal internal activity may begin naturally during periods of stress that result in decreased blood flow. One result is a headache; another result may be a change in the ionic balance in a local region of the brain that causes the underlying neurons to discharge spontaneously. This internally generated activity often leads to perceptions.

Some 10 percent of us suffer migraine headaches at one time or another during our lifetime, and about half of the time such headaches involve the visual areas of the brain. In these headaches, when the visual areas become active, the individual sees a spectacular array of scintillating bars and corners; the display as a whole has the appearance of pre-20th-century fortifications seen from above. The form of the fortification figures provides strong clues to the kind of feature extraction conducted by the human visual system. Although reports of these displays go back many centuries, it was only some 100 years ago that their significance was recognized when George Biddell Airy, the British astronomer royal, and his son Hubert Airy, a physician, provided accurate accounts of their own visual displays. In a remarkable paper published in 1870 Hubert Airy related the displays to the known structure of the brain and concluded by recognizing that the spontaneous perceptions probably represented a realistic "photograph" of processing in the brain.

The visual displays that arise during ophthalmic migraines can take several forms, but only the classical type experienced by the Airys and reported in their papers [*see illustration on opposite page*] is sufficiently clear and well documented to provide reliable evidence on feature extraction in the human visual system. I should like to describe this type of display in some detail, basing my quantitative results largely on observations provided by one person (my wife), with supporting data obtained from several other people. One of the others was the late neurophysiologist W. S. McCulloch, who recognized the importance of his own migraines and provided a photograph of a sketch of what he saw during one of his attacks. All these people, and others described in the literature, saw their displays equally well with either eye. In view of the basic neuroanatomy of the visual system, this means that the visual effects must have been the result of neuronal activity in the brain rather than in the eye itself.

The visual disturbance usually precedes the headache and can occur without any headache. It generally begins near the center of the visual field as a small, gray area with indefinite boundaries. If this area first appears during reading, as it often does, then the migraine is first noticed when words are lost in a region of "shaded darkness." During the next few minutes the gray area slowly expands into a horseshoe, with bright zigzag lines appearing at the expanding outer edge. These lines are small at first and grow as the blind area expands and moves outward toward the periphery of the visual field. The rate of expansion of both the arc formed by the zigzag lines and its associated band of blindness is quite slow: some 20 minutes can elapse between their initial appearance near the center of the visual field and their expansion beyond its limit. It is then that the headache usually begins, behind or above the eyes. It is the only unpleasant aftereffect of a spectacular visual display.

Because the band of activity moves so slowly across the visual field, the general shape and overall properties of the fortification are easy to chart. The subject fixes his gaze on a mark on a piece of paper and then sketches the projected

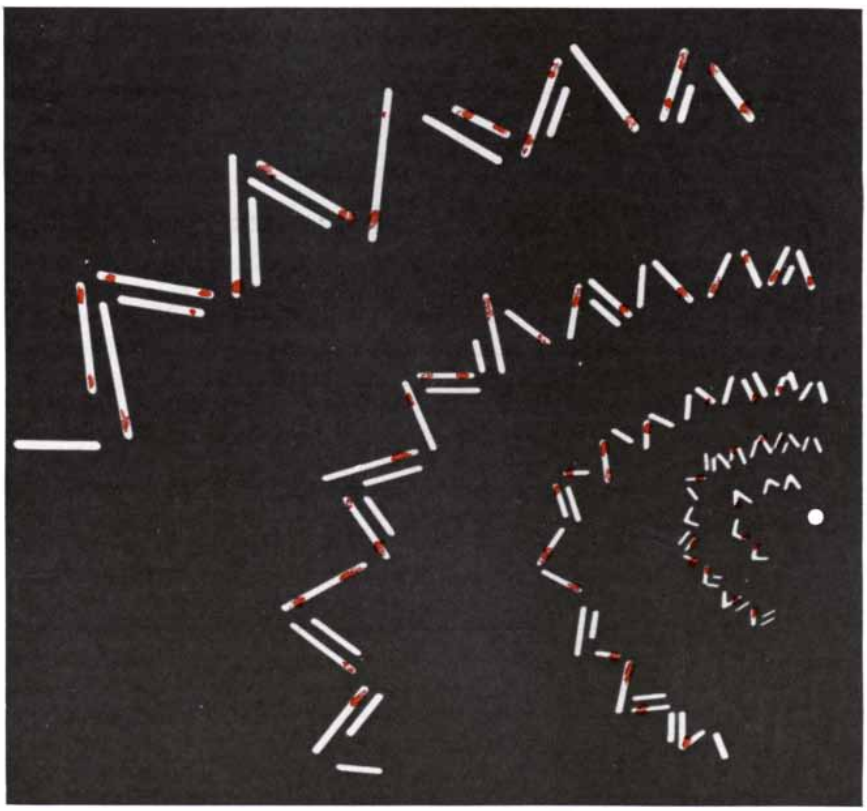
outlines of the figures he sees [*see illustration below*]. Combining several such drawings, one can also record the general form the arcs take as they expand across the visual field [*see top illustration on opposite page*]. The arcs drawn by Hubert Airy 100 years ago almost exactly match those of my principal subject, and they are the basis of the whole-field drawings. The only additional feature that has been reported is a slightly more complex arc, shaped somewhat like a double *C*.

A plot of successive arcs resembles a map of an electric field around a point source, and many people have suggested that the expanding arc represents a wave of excitation radiating from a single region of the visual cortex. The noted neuropsychologist K. S. Lashley estimated on the basis of his own experience with migraine fortifications a propagation rate of three millimeters (about an eighth of an inch) per minute. In order to arrive at such an estimate he assumed that the excitation spread at a constant rate even though the arcs themselves appeared to expand with increasing speed as they grew larger. In view of the way the visual field is mapped on the cortex, the assumption is quite reasonable. A constant propagation rate of excitation would indeed cause the larger arcs to grow faster, because the peripheral part of the visual field is represented by a diminishing amount of cerebral cortex: since there is progressively less cortex per degree of visual field as one moves from the field's central region to its outer margin, a wave moving at a constant rate across the cortex will appear to move faster as it moves toward the peripheral field. My own calculation of the maximum rate of propagation of this wave, based on recent electrophysiological maps of the topography of the visual field in the human striate cortex, is 3.3 millimeters per minute, in good agreement with Lashley's earlier estimate.

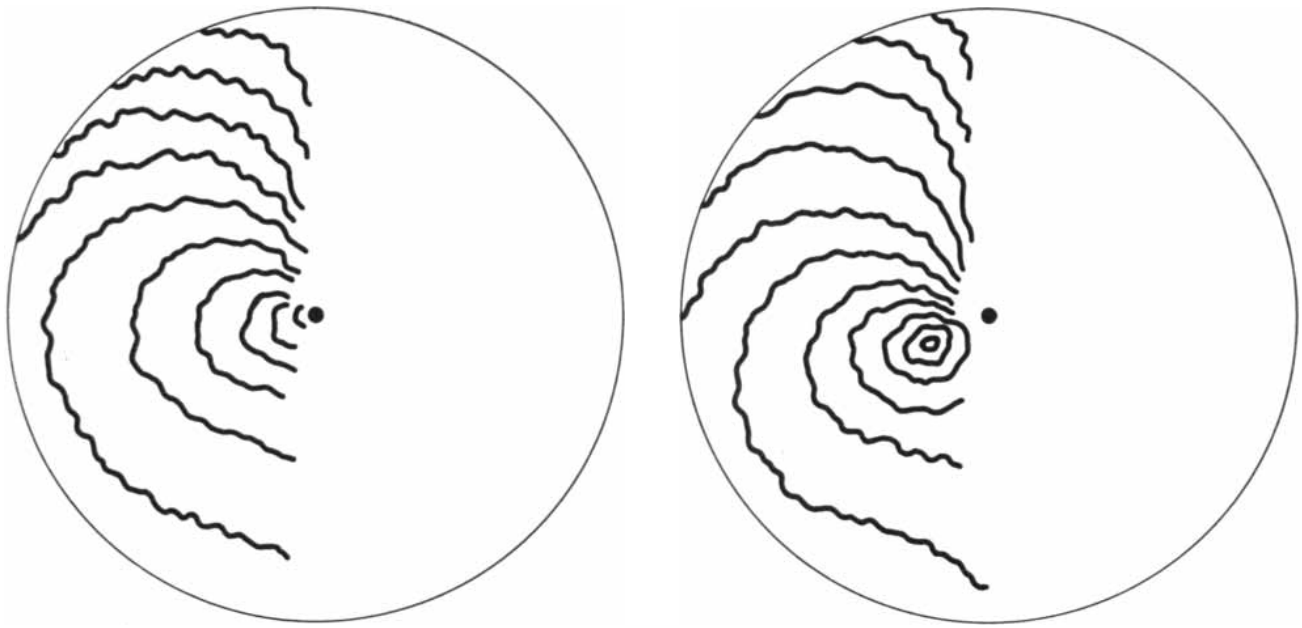
Although the arc of fortifications is clearly visible at any given instant, the details of the lines comprising the arc itself are hard to fix in the mind or capture on paper. For those of us engaged in analyzing the mechanisms of the brain, it is these details that are of the most interest [*see bottom illustration on opposite page*]. In the simplest type of fortification the arc is serrated and consists of two lines about as bright as an overhead fluorescent lamp. Each member of the pair of lines oscillates in brightness at about five cycles per second, with all the inside lines "on" when all the outside lines are "off," and vice versa. This synchronization causes the entire arc to reverberate with what is described as a "boiling" or "rolling" motion. Such behavior suggests an underlying neural network of reciprocal inhibition, in which the depression of activity in one local region would enhance the spontaneous neural activity in adjacent regions. If this antagonistic activity were triggered by the expanding boundary of the cortical disturbance, then the disappearance of one set of lines at the outside margin of the disturbance would be followed by their reappearance inside the expanding boundary in what had previously been a depressed region.

In addition to the obvious spatial properties of the display, such as the increasing size of the lines as the arcs move toward the periphery, there are also subtle effects related to color, line orientation and the spacing between the lines. It is difficult to provide more than qualitative impressions of most of these details. When the fortifications are complex, only a general impression of the display can be recorded; the details are not necessarily accurate. The arc may become a grid: a hatched band that seems to consist of five or six parallel lines, although it is difficult to make an actual count because the bands sweep across the figure toward the advancing margin and are constantly renewed at the inner edge. Between the lines of the grid faint red, yellow and blue streaks often appear, whereas on the lines themselves these colors may be seen only at the tips ("like match heads") when the display is of the simpler variety. Both George Airy and his son reported seeing red, blue and yellow in that order of frequency; they saw green only rarely, and green was never observed by my main subject.

Within each arc of fortification figures there is a transient band of blindness. It becomes apparent when the lines are being sketched because the end of the pencil simply becomes invisible as it enters the band! If the subject is not aware that there is something within the visual field that is not visible, the region of blindness is easy to miss, in part because it may be "filled in." Lashley told of a time when in the course of a conversation he glanced just to the right of his friend's face and the face disappeared. His friend's shoulders and necktie were still visible, but the vertical stripes in the wallpaper behind him now seemed to extend right down to the



SERRATED ARCS seen by the author's primary subject (his wife) are redrawn from her sketch, in which the white lines have yellow, orange and red segments, particularly near the ends, and a few streaks of blue. Ordinarily one arc is seen at a time, its constituent lines flickering to give a "boiling" or "rolling" motion. The white dot is the point of fixation.

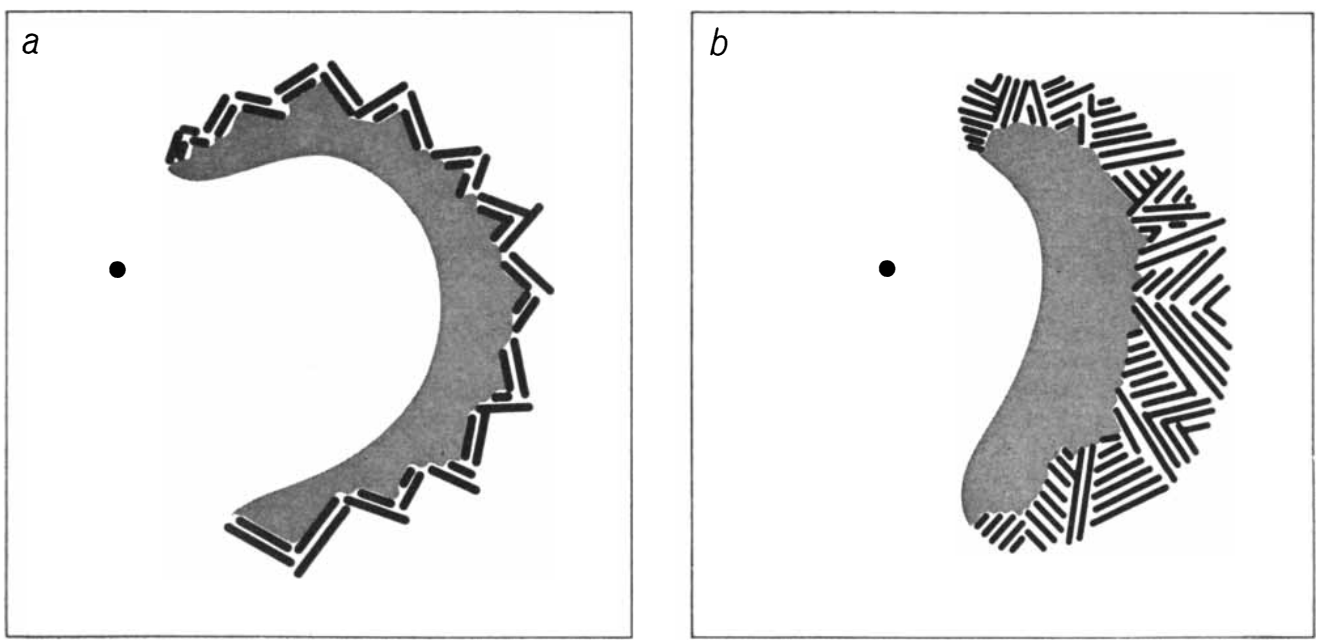


SUCCESSIVE ARCS expand across half of the visual field, as shown in two diagrams based on Airy's two sets of arcs. The disturbance may take 20 or 25 minutes to expand from a fuzzy gray area near the fixation point (*dot*) to the outer limit of the visual field.

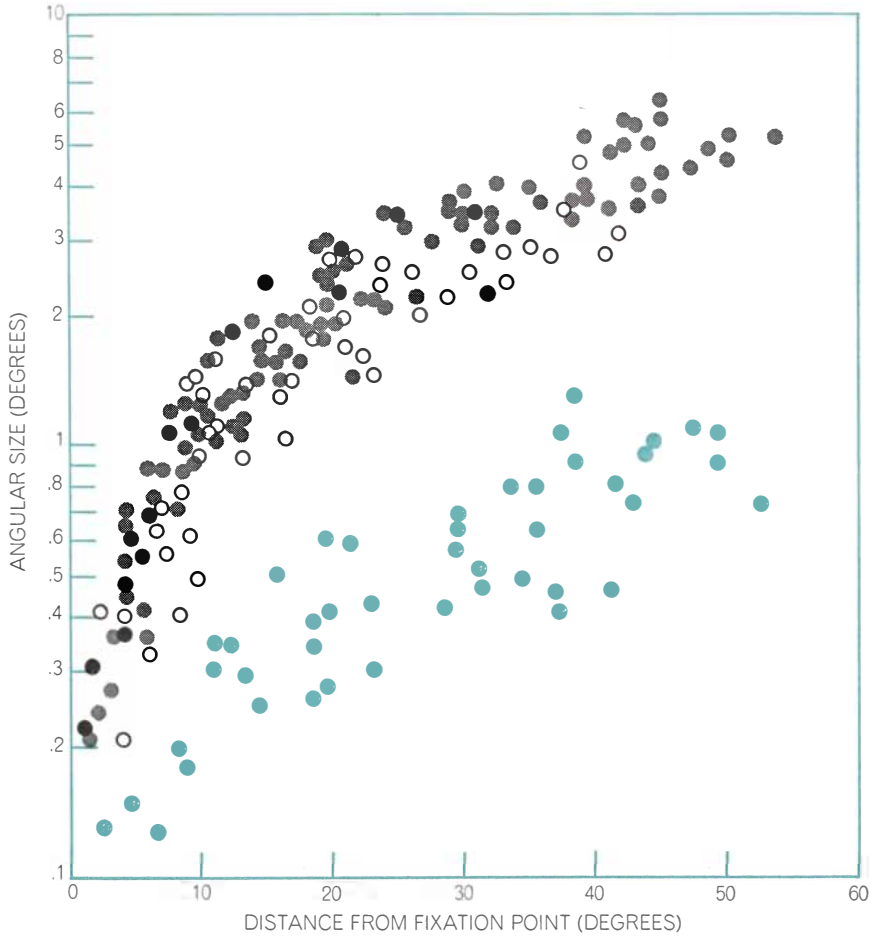
necktie. This filling-in phenomenon is the consequence of some higher-level process that presents an interesting and still unsolved puzzle.

Considering the recent direct evidence obtained by the neurophysiologists from single cells in the visual cortex of the cat and monkey brain, it is of interest to compare their description of feature detectors with some of the properties of the fortification figures. For example, David H. Hubel and T. N. Wiesel have shown that one kind of feature extraction conducted by the visual cortex in their experimental animals is the detection of lines of a particular length and orientation. The fortification figures suggest that the human visual system performs a similar type of analysis. The expanding boundary of cortical disturbance is actually a set of discrete lines in visual space. If the length of these lines is charted over a wide range of positions in the visual field, it is seen that the lines are small near the central part of the field and become steadily larger with increasing distance from the center. On the basis of current knowledge of the mapping of the visual field onto the human cortex one can estimate how much distance on the cortex is represented by one of these lines. My calculations yield an estimate of about 1.2 millimeters of cortical distance for each line, regardless of the line's position in the visual field; it simply appears larger farther out.

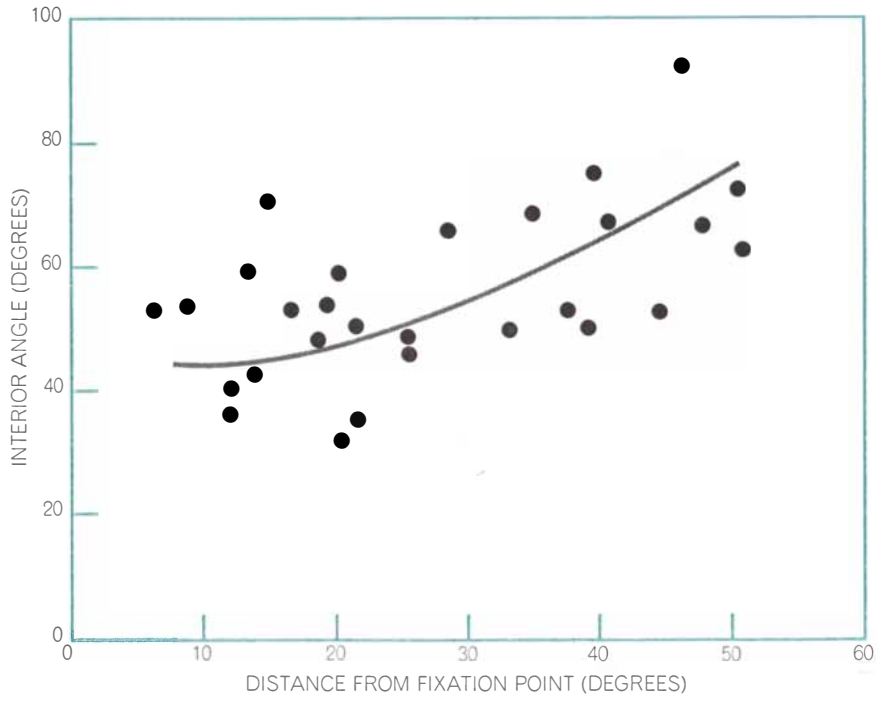
The constant size of these line lengths on the cortex suggests that the cortex it-



DETAILED FORM of two types of figure is apparent in these diagrams, in which individual fortifications are "stopped," without their customary flickering or rolling motion. The contrast tends to be greater in the simple type of arc (*a*) than in the more complex one (*b*). In each case the gray area represents a transient region of blindness that moves outward roughly parallel to the expanding arc.



LENGTH AND WIDTH of lines in three displays are plotted for different positions in the visual field. The angular lengths (*black, gray and open circles*) increase with distance from the center of vision but all represent about 1.2 millimeters on the cortex. The width (which is equivalent to the separation between lines) is about a fourth as large (*color*).



INNER ANGLE between two lines meeting to form a serration was measured at various points in the field. The average angle increased from 45 degrees near the center to 70 degrees.

self is organized into discrete "elements" of constant size. In fact, Vernon Mountcastle, Hubel and Wiesel and others have shown that brain areas in the visual pathway up to and including the cortex seem to possess "columns" of cells that have certain triggering features in common. In the monkey visual area these columns average .2 to .3 millimeter in diameter, or a fifth as large as my estimates based on line length. The discrepancy between the results obtained for the monkey and for man disappears, however, if the line elements seen during migraines represent not the output of individual columns but rather pools of columnar activity—perhaps a summation of or convergence from several columnar units. The size of the units contributing to the pool would presumably be indicated by their smallest dimension, which would be the width or separation of the lines. The distance between the lines is about a fourth of the line length [*see top illustration at left*]; hence the simplest columnar units presumably measure about .3 millimeter in diameter in man.

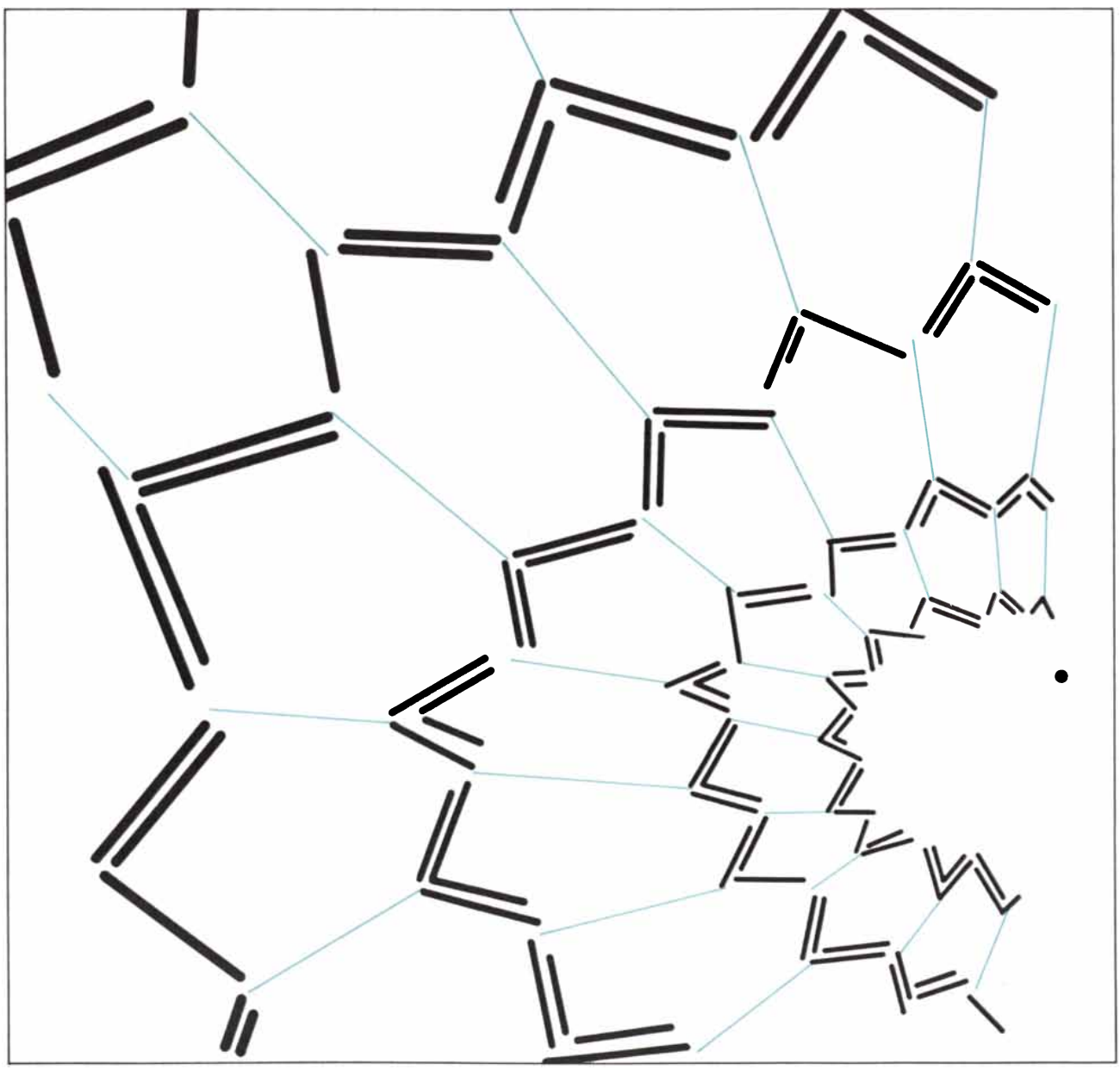
In addition to "line detectors," neurophysiologists find more complex analyzers ("corner detectors" and "tongue detectors") in the same and neighboring visual areas of the cat and monkey cortex. These complex analyzers do not seem to be present in the human cortex at the level of the migraine disturbance. The serrated edges of the fortifications do give the appearance of corners, but the neurons apparently do not detect corners as such. Most of the lines form not precise corners but rather parts of a disjointed *T*, with one line extending beyond its neighbor. Moreover, only a small fraction of the lines are actually joined at their end points, and the gaps separating the end points seem to be located at random. The gaps are seen most easily when the tips of the lines are colored, and the colors help to show that these are blurred intersections rather than true corners.

An interesting size effect has come to light in this connection. The lines, their colored end points and the gaps between them were seen with more clarity when my subject projected the display onto a surface about eight inches or less from her eyes than when she projected it onto a wall a yard or two away, even though their apparent size was smaller. This sharpening of the visual display was of course not caused by optical factors such as better focusing by the lens; the display is in the brain and not the result of light passing into the eye. The sharpness of the display must have been caused by a change within the brain itself, such as

a change in the grain of the visual system brought about by the convergence of the eyes.

The reduction of apparent size was to be expected: when the eyes are converged to fixate a near object, there is an illusory reduction in the size of a fixed retinal image, an effect called size micropsia. (The illusion is striking when a card on which an afterimage is projected is brought closer and closer to the eyes.) What is strange in the case of the fortifications is that even though the lines seen during a migraine attack may *appear* to the observer to become smaller when the eyes are converged, their true average angular size (determined by the experimenter's measuring them on a sketch or presenting sample lines for comparison) may actually increase at the nearer fixation distance; the angular eccentricity of the arc increases at the same time. The most accurate measurements indicate that the magnitude of this "reverse size effect" is an enlargement of some 25 percent when fixation is reduced from about 48 inches to about eight inches. Because the changes in the angular size of these internal images are the opposite of the changes seen with images of external objects, one infers that the act of eye convergence leads to modification in the visual pathway at the site of the cortical disturbance or between the eye and the site of the disturbance.

If the serrations in the boundary of a fortification figure do not represent the activity of corner detectors, why is the boundary serrated? Why is it not a smooth line, reflecting the presumably smooth and continuous front of the expanding cortical disturbance? The appearance of serrations supports the notion that the neural substrate of the cortex is organized into discrete elements at a level at or above that of individual neurons. If that is the case, a smooth line traced across the cortex would move from one discrete element to the next,



HONEYCOMB PATTERN emerges when a number of arcs are plotted together, following the data from the two illustrations on the opposite page, and approximately radial lines (*color*) are added. The honeycomb and the tendency for the inner angle between lines to approximate 60 degrees are suggestive of hexagonal organization. But why are the sides of the cells (*color*) never seen?

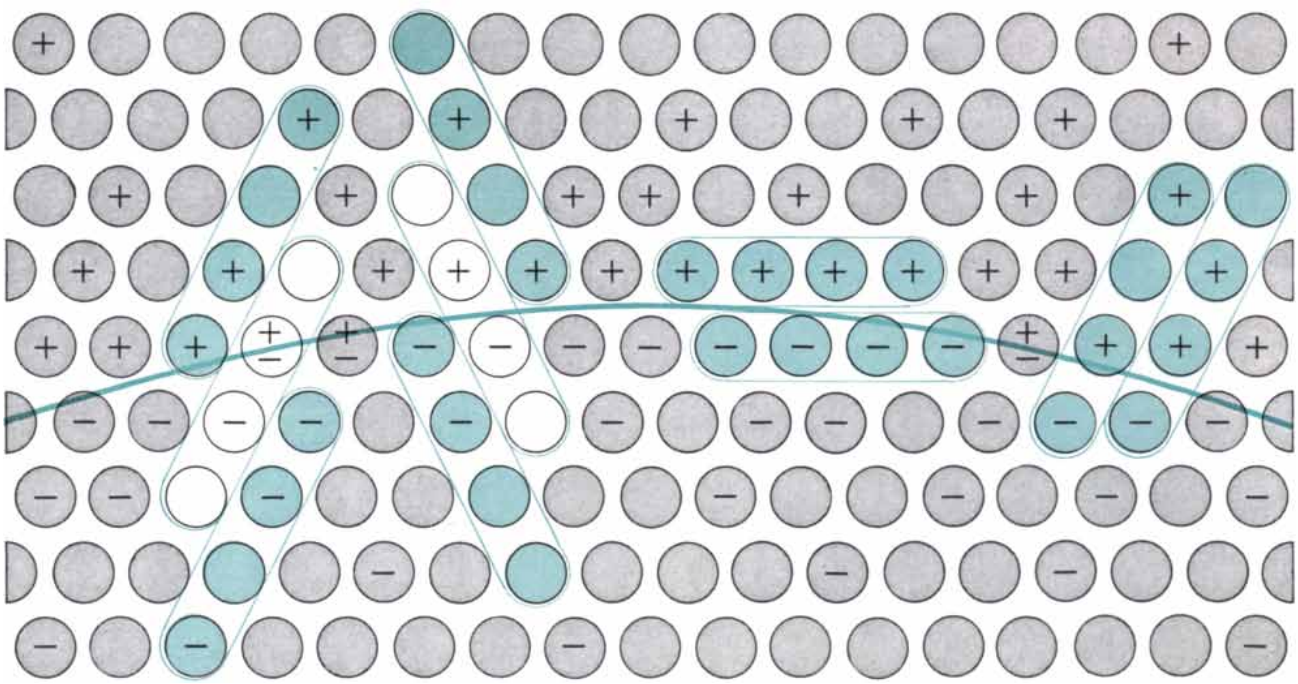
and each element could have an entirely different representation in the visual field. These elements should correspond to clusters of cortical cells that have certain triggering features in common, such as the same line orientation in a given region of the visual field. Neurophysiologists have compiled evidence that such clusters exist, but it has been difficult to map a long succession of clusters with direct recording techniques and thus to determine how the clusters are organized in the cortex. In this respect the migraine fortification is an excellent natural experiment: the advancing waves of disturbance draw continuous traces across the cortex and in less than half an hour reveal part of the secret of its neuronal organization.

All fortification figures have two striking and significant properties. One is revealed when the inner angle between the two lines forming a serration is measured over the entire visual field. The angle is almost always acute; it is about 45 degrees near the center of the field, increases to about 70 degrees at the periphery and averages about 60 degrees [*see bottom illustration on page* 92]. The other property is the absence of radial lines perpendicular to the boundary of the fortifications. The first property suggests that the neuronal substrate of line detectors in the human visual cortex must be organized into a regular lattice such that the relative orientation of each line to its neighbor is about 60 degrees. To the extent that the lattice is regular within a local region of the field, each line element could have only one of three orientations; it would therefore sample visual space in the pattern of an asterisk (*). The second property confirms this notion, because only some such spatial order in the cortex can explain a response so selective that it leaves out all radial lines.

Let me develop this reasoning in more detail. Normally only one serrated arc is seen at a time, but one can plot a succession of the arcs, making both the length of the lines and the angles between them conform to the experimental evidence [*see illustration on preceding page*]. If one then adds radial lines [*color*], a distorted honeycomb structure is revealed. The radial lines, however, are precisely the ones that are never seen. Why? The explanation lies in the nature of perceptual processes, which respond primarily to local differences. For example, it is not the luminous intensity inside a homogeneous square that determines how bright the square appears to be. The critical factor is the magnitude of the step in luminance at the edge of the square. A piece of gray paper therefore appears either dark or light depending on its background [see "The Perception of Neutral Colors," by Hans Wallach; SCIENTIFIC AMERICAN, January, 1963]. In other words, the visual system looks only at both sides of the edge and "fills in" a description of the remaining area by extrapolation or inference.

Now consider a hypothetical wave front of electrical activity advancing across the cortex [*see illustration below*]. The electrical gradient associated with the wave front is defined by the density of plus and minus signs; the circles represent the individual components whose activity is pooled to form the clusters, or line elements, indicated by the colored outlines. Consider three possible orientations of these elements: perpendicular, parallel and oblique to the wave front.

Two adjacent line elements perpendicular to the wave front are likely to have identical electrical activity; there is thus no basis for a differential response between them, and so they are not "seen." Line elements parallel to the wave front—one on each side of it—have



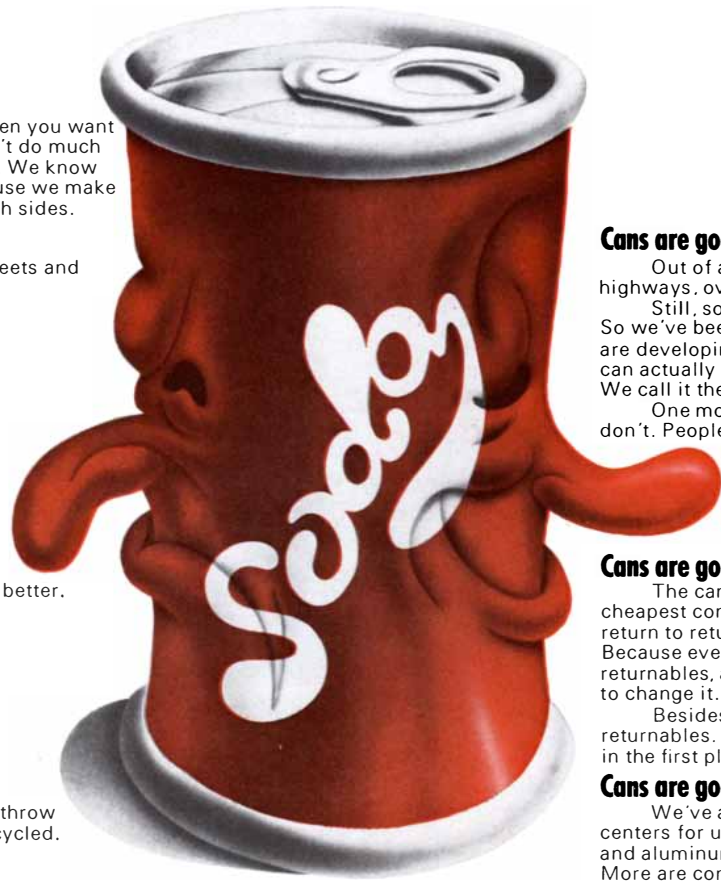
NEURAL SUBSTRATE affected by a migraine disturbance is diagrammed to illustrate how electrical activity results in the perception of lines with only certain orientations. The density of plus and minus signs represents the electrical gradient associated with the expanding wave front (*colored arc*) of the migraine disturbance. The circles are brain cells. Four cells in line form a line element. Two elements (*color*) at the right are perpendicular to the wave front. In this orientation the total activity of the two elements is the same; there is no basis for a differential response in the cortex and such elements are not seen. Elements parallel to the wave front may be seen on occasion, but only when the gradient lies athwart an element, not when it lies between them as shown here. Elements oblique to the wave front (*left*) are the most visible: active elements (*color*) above and below the wave front yield differential responses with respect to the elements with zero net activity (*white*) between them. These are the elements that form the serrations.

Cans.
Bad Guys or Good Guys?

A can is a nice thing when you want a soda or a beer. But it doesn't do much for a landscape or a highway. We know that better than anyone because we make cans. So here's the story. Both sides.

Cans are bad guys.

Cans are all over the streets and highways. Cans cause litter.



Cans are bad guys.

Returnable bottles were better. Return to returnables.

Cans are bad guys.

You use them once and throw them away. They can't be recycled.

Cans are good guys.

Out of all the litter on the streets and highways, over 83% isn't cans.

Still, somebody has to do something. So we've been working with people who are developing a fantastic machine that can actually pick the litter off the roads. We call it the octopus.

One more thing about litter: Please don't. People litter. Not cans.

Cans are good guys.

The can is one of the safest, cleanest, cheapest containers ever invented. If we return to returnables, prices will go up. Because everything is set up for non-returnables, and it will cost money and jobs to change it.

Besides, people don't return returnables. That's why cans happened in the first place.

Cans are good guys.

We've already set up recycling centers for used cans. (All used cans. Steel and aluminum. Beer and soda and food.) More are coming. This costs us money, but it doesn't cost you anything. You bring us the cans and we'll recycle them.

We know it would be easier and better if all you had to do was throw your cans in a garbage pail. So we're supporting the development of automated machines that can pick cans out of the rest of the garbage. And we hope that eventually every can in every city will be recycled and used to make new cans. You won't see it tomorrow. But you will see it. We promise you that.

We have more to lose than you do.

The Can People

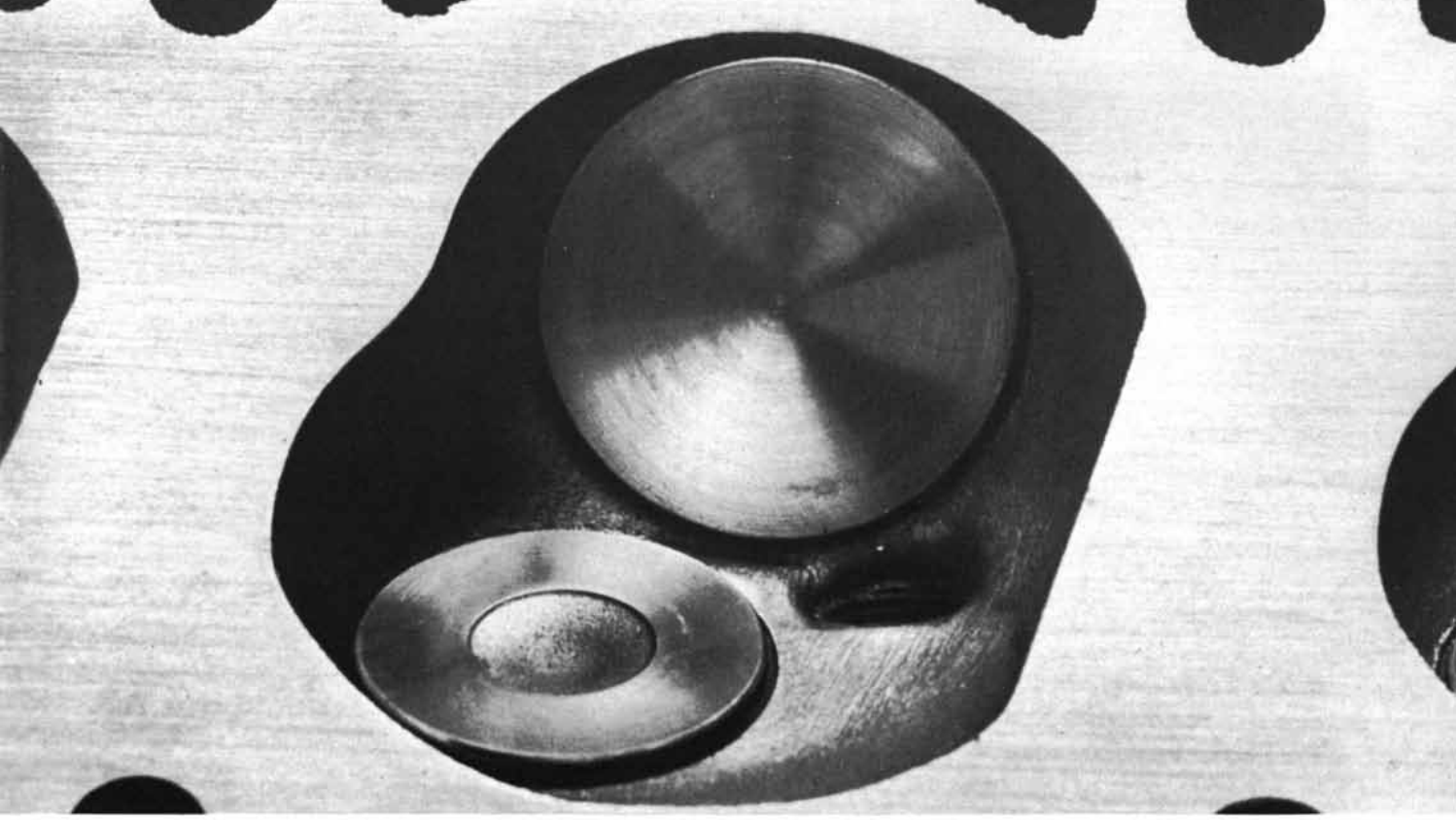
We care more than you do. We have to.

The Can People: American Can Company, Continental Can Company, National Can Corporation, The Heekin Can Company.

quite different electrical activity (are very positive or very negative) and one might expect them to be quite visible. Lines parallel to the expanding arc are actually seen infrequently in fortifications, however. The explanation lies in the nature of the neuronal response to the electrical gradient. Neurons comprising an element are activated when the element has either a positive or a negative ionic imbalance; the polarity at the gradient is immaterial. Therefore when the wave front lies precisely between two parallel elements, the activity of the two elements is equal, there is no basis for a differential response and the two adjacent parallel elements will not be seen. Only when the wave front lies directly on one element should the two neighboring elements be seen, because then their large activity is in contrast to the inactivity of the element between them that is split by the wave front. Since an element will be precisely split only a small fraction of the time, parallel elements will seldom be visible. And if the gradient is shallow, they may not be visible at all.

It is the third kind of element, an element oblique to the wave front, that is most likely to be seen. In this orientation there are two possible active elements, one on the positive side and one on the negative side. There is a clear difference between each such element and the intermediate, neutral one between them. Because the contrast in activity between two such oblique elements is largely independent of the exact position and extent of the electrical gradient, the lines representing their activity should be the ones most commonly observed. They are the lines that form the typical serrations.

Such speculation on the detailed neuronal organization of part of the brain may seem premature, but it is in keeping with everything that is being learned about the visual cortex. In this apparently undifferentiated mass of brain tissue, neuronal specificity appears to be the rule rather than the exception. Moreover, a hexagonal lattice, such as might be represented by the honeycomb structure I have described, is the commonest arrangement for the packing of cellular structures in living systems, as D'Arcy Wentworth Thompson showed so elegantly in his celebrated treatise *On Growth and Form.* Such a structure is indeed a natural consequence of the packing of a well-ordered array of cylindrical elements. Would it be surprising, then, if the neural structure of the human brain also follows this simple, basic pattern?



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THREE BULLHEAD CATFISH occupy a section of pipe in a laboratory tank. The largest of the three fish, at the bottom of the pipe, is recognized by the other two fish as being the dominant one in the tank, and it is usually the exclusive occupant of the shelter. In this instance, however, the two subordinate fish have sought refuge in the pipe after detecting the odor of an unfamiliar bullhead.

APPROACH OF STRANGE BULLHEAD induces an aggressive response from the dominant fish, as is shown by its gaping mouth display. The dominant fish often attacks the intruder, but its tankmates, with their mouths pacifically shut, usually stay in shelter.

The Chemical Languages of Fishes

Many fishes have exquisitely sensitive organs of smell. Experiments with catfishes demonstrate that they use this sense for such social purposes as labeling the winners and losers of hierarchical fights

by John H. Todd

The fishes, of which there are some 25,000 living species, are unrivaled among the vertebrates in the ability to adapt to unpromising living conditions. They have managed to invade and occupy some of the earth's most extreme and inhospitable environments. There are catfishes in South America and in the Himalayas that spend their lives clinging to sheer rock faces in torrential mountain streams. *Anabas,* the "climbing perch" of the Orient, on occasion leaves its water habitat to walk about on land breathing air and even climbs low branches of trees in search of prey. The "annual" fish of Africa and South America, so called because its lifetime is only a single season, regularly shows up each year in tiny temporary pools that are limited to the wet season in semiarid areas. Perhaps the strangest of all the fishes are the bizarre creatures that live out their entire existence in the perpetual darkness of the ocean depths or murky waters. Most surprising, some of these animals, although sightless or nearly so, have developed sophisticated social behavior rivaling that of the higher animals in complexity.

The explanation is that these fishes have established communication, the prime necessity for social life, through their chemical senses. In many species the receptors and associated brain centers for taste and smell dominate the sensory side of the nervous system, overshadowing the optic lobes. Some fishes have been found to possess almost incredible chemosensory acuity. Harold Teichmann of the University of Giessen was able to condition eels to respond to concentrations of alcohol so dilute that he estimated the animals' olfactory receptors could not have received more than a few molecules.

I was led into the fascinating investigation of chemical communication among fishes by a study of the behavior of bullheads, or catfish, that I began at the University of Michigan under the stimulating direction of John E. Bardach. The bullhead, a predominantly nocturnal animal, has poor vision but highly developed senses of smell and taste. Its nose is almost as keen as the eel's, and its entire body is covered with hundreds of thousands of taste buds. Many years ago George Howard Parker of Harvard University had concluded from studies of the feeding behavior of bullheads that they found their way to food in the water by smelling it at a distance. I repeated and enlarged on his investigation and found that it was not smell that led bullheads to food. Blinded bullheads that had been deprived of their olfactory receptors were able to swim directly to a food source in still water. The guiding factor proved to be detection of the chemical stimulus from the distant food by the taste buds on the bullhead's body; this was demonstrated by the fact that when the taste buds on one side of the body were destroyed by surgery, the fish had difficulty finding the food and was able to do so only by constantly looping to the side where the taste buds were intact.

I was confronted then with a puzzling question: If the bullhead's remarkable sense of smell was not needed for finding food, what functions did it perform? By accident I was soon given a clue. One busy day, having an extra fish on hand without an aquarium in which to house it separately, I put the fish in a 50-gallon tank with a blinded bullhead that had occupied it alone for about a month. Immediately the two fish broke into frenzied activity, thrusting their tails against each other, quivering, opening their mouths in fierce displays and tearing at each other. I had to remove the newly introduced fish to prevent their seriously injuring each other.

These two bullheads were of the same species. When I later put a fish of a different species (but about the same size) in the tank with the resident bullhead, the resident did not attack it. In further experiments it developed that the blinded bullhead became excited and aggressive when water from the aquarium of the fish with which it had fought was introduced into its tank, but it was not aroused by a similar introduction of water from the aquarium of the different species. Evidently the blinded bullhead was able to recognize its own species from some chemical cue in the water. The animal made a surprising response to the next experiment: when water was introduced from the aquarium of a bullhead of the same species but not the fish with which the resident had fought, the resident circled the water area for several minutes but did not attack it and indicated a gradually waning interest in it.

The results of these experiments suggested that the chemical signals to which the blinded bullhead responded carried more than one message: the recipient not only was able to identify an individual of its own species but also received a signal that might identify the intruder as an individual representing a threat of some kind. Plainly the chemically sensitive bullheads must use their gift for purposes other than finding food. This realization inspired a series of investigations of fishes' communication and social behavior that I have carried out with various collaborators at the University of Michigan, San Diego State College and most recently at the Woods Hole Oceanographic Institution.

I shall relate first what we have

learned about communication of the most obvious kind: that having to do with sexual behavior. At San Diego State, Jack Nelson and I made extensive laboratory studies of the subject with two species of blennies, small fishes that abound in the tidal waters along the coast of California.

There had been earlier pioneering investigations in the area. It was George MacGinitie of the California Institute of Technology who first discovered some 35 years ago that fish use pheromones—chemical signals—for communication, as insects and some other animals do [see "Pheromones," by Edward O. Wilson; SCIENTIFIC AMERICAN, May, 1963]. MacGinitie studied the blind goby *Typhlogobius californiensis,* a small intertidal fish that loses its eyesight when young and spends its life in a burrow built by the mud-dwelling ghost shrimp. This fish, male or female, is extremely aggressive toward members of its own sex, and it will tolerate only a member of the opposite sex as a burrow-mate. Apparently a male and a female goby pair up early, before they are sexually mature, and usually remain paired for life. If an intruder invades the burrow, the resident of the same sex engages it in vicious combat that usually ends with the death of one or the other; if the intruder defeats the resident, it is accepted by the other inhabitant as if there had been no change.

MacGinitie found by experiment that the blind goby recognized the sex of a member of its species by means of a chemical signal. His experiment consisted in placing a goby in a small bag, puncturing the bag with a pin so that water could flow out of it, and then inserting the bag in a burrow occupied by a blind goby pair. When the odor from the enclosed fish reached the pair, the member of the same sex as the enclosed fish would immediately attack the bag.

Our own work with blennies was prompted by recent findings of George Losey of the Scripps Institution of Oceanography. He had shown that a male blenny could be stimulated to courtship behavior by exposure to water from a tank in which a pair of blennies of the same species were engaged in intensive courting or mating. Losey's research raised several intriguing questions, and Nelson and I began an investigation of the sexual behavior of two species of the genus *Hypsoblennius*—the mussel blenny (*H. jenkinsi*) and the tide-pool blenny (*H. gilberti*)—that live in the tidal pools along the seacoast at La Jolla, the site of the Scripps Institution.

Both species bred readily in laboratory tanks simulating their natural environment, and we analyzed the details of their sexual and parental behavior. This behavior proved to be almost identical in the two species: in the building or selection of nests, courtship displays, actions during breeding and parental care there was little difference between the *jenkinsi* and the *gilberti* blennies. Indeed, when we tried to pair one species with the other, the mussel blenny males even showed some interest in courting tide-pool blenny females. This courtship was not consummated, however, by actual breeding. Furthermore, one had to find some explanation for the fact that the two species do not interbreed in nature, although they inhabit the same tide pools. The small differences in their action patterns that we observed did not seem sufficient to account for the species' isolation from each other. Evidently there must be signals of some kind that distinguished the species and prevented interbreeding.

We looked first for indications of how important visual stimuli alone were in invoking sexual behavior. Males and females were placed individually in sealed glass jars to exclude the transmission of all stimuli except the visual, and we observed their responses to one another. In this situation the males still courted females and usually made attacking moves toward males of their own kind. In the main each species ignored the blennies of the other species, except that the mussel blenny males did often court tide-pool blenny females [*see upper illustration on page 108*]. Hence apart from this one exception the blennies seemed to be able to recognize sex and species visually. Since the females, unlike the males, are similar in size and color, it was perhaps not too surprising that the male mussel blennies indiscriminately courted females of both species. Other signals seem to be indicated.

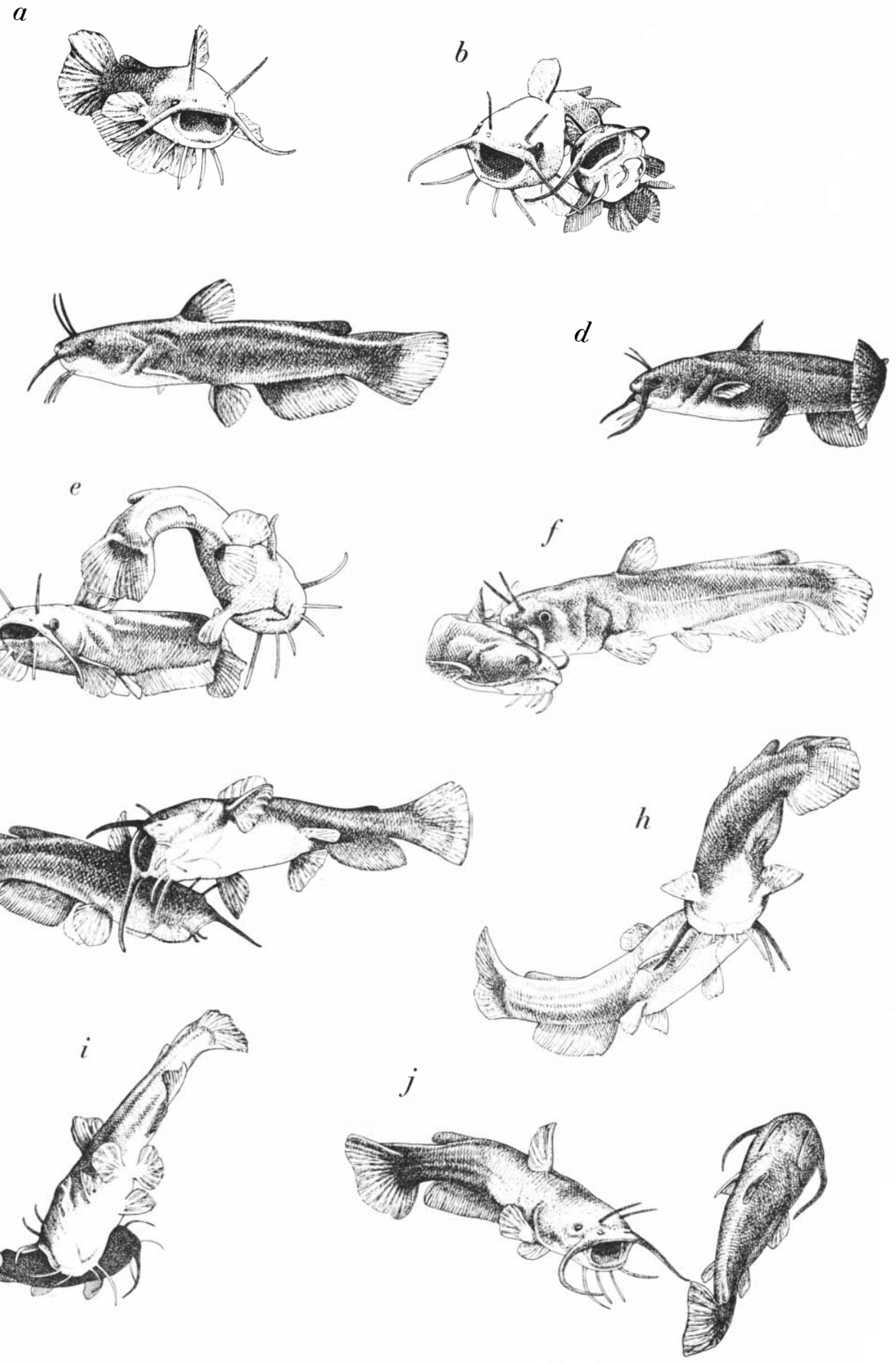
We then proceeded to hunt for chemical signals. The problem was complicated by the fact that we wanted to detect signals from the male and from the females of both species. Other signals had suggested to him that pheromones were produced only by the male. After many months of work and a number of unsuccessful attempts Nelson eventually developed a method for collecting the chemical emissions from an individual of either sex and presenting this uncontaminated material to a test animal. As the test animals we used mussel blenny males, since this provided us with the opportunity to find out if they were guided by a chemical signal to make a discrimination between species that they were unable to make visually. The mussel blenny male was first shown a sexually responsive female of the same species to determine whether or not he would show courtship behavior. If he did, he was then tested for his reactions to measured (100 milliliter) samples of water from various sources: a recently courted mussel blenny female, an uncourted mussel female, a courting mussel male, a courted tide-pool female or just plain seawater. The samples were uncontaminated by water that had been in contact with fish of the opposite sex. This was achieved by having the two courting fish separated by a glass barrier inside the tank.

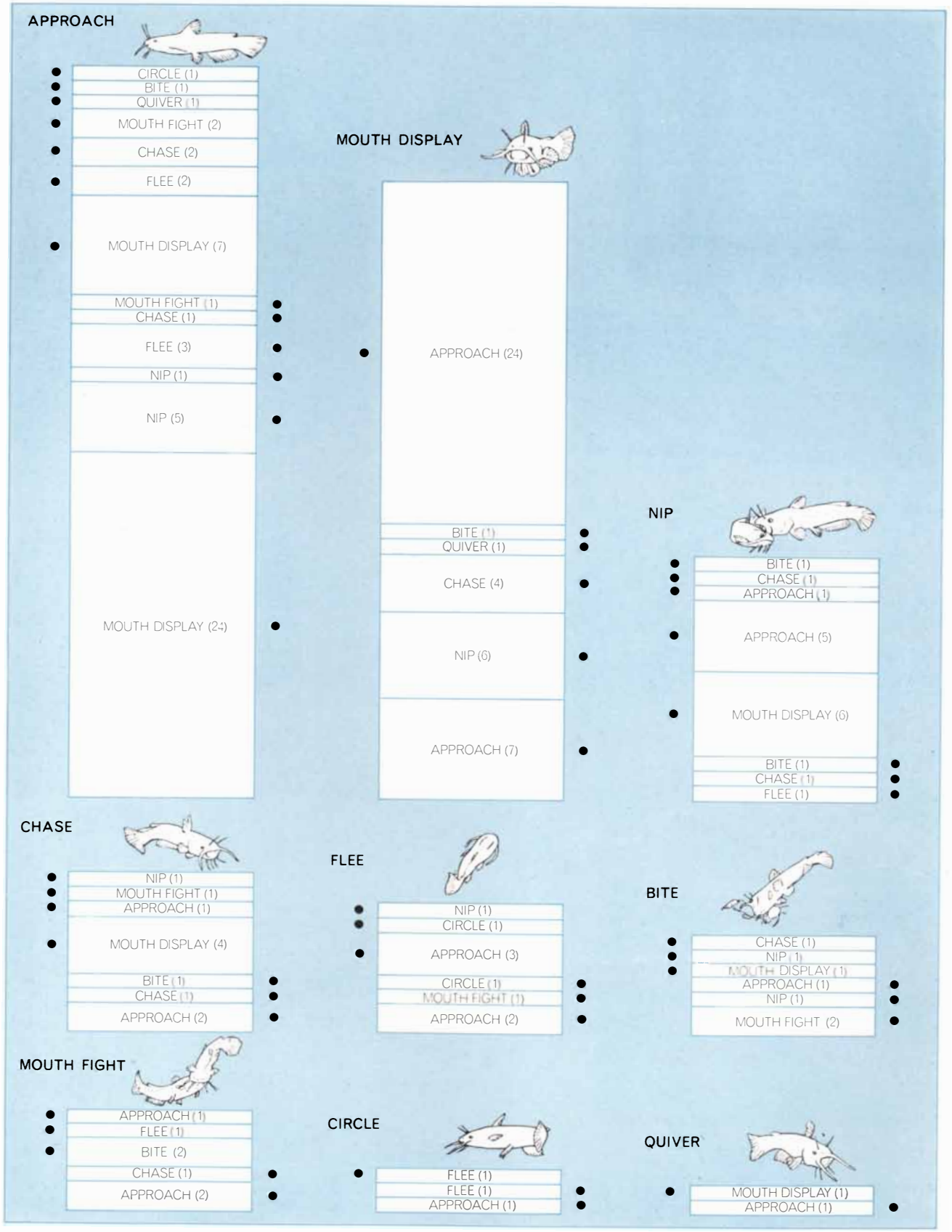
Fortunately it was possible to determine unambiguously if the fish's response was due to a chemical signal; there are certain courtship actions in the blenny ("head jerking" and "quivering") that are associated with strong sexual motivation and that could be triggered by pheromones alone.

It turned out that in a high proportion of the tests the mussel blenny males did show this courting behavior when they were exposed to water that had bathed a courted female of their own species (no visual cues being present). They also responded to males of their own species, although much less often, by approaching water taken from the jar housing such a male. Presented with water from the jar of a tide-pool blenny female or with plain seawater, however, the mussel blenny male in almost every case made no response [*see lower illustration on page 108*].

Thus the results indicate that a pheromone produced by the female during courtship is the signal that sets the two species apart; the species difference in

AGONISTIC BEHAVIOR of the bullhead ranges from mild to severe; some typical actions are illustrated on the opposite page. Mouth display varies considerably in intensity: a low-key form (*a*) contrasts with more extreme displays (*b, left, and j*). Both approaching (*c*) and circling (*d*) occur in interactions of various intensities. Intermediate in intensity are the tail thrust (*e, top*), lateral display (*b, right*) and nip (*f*), all common actions among equals. The head thrust (*g*), mouth fight (*h*) and bite (*i*) are actions of greater intensity. Encounters between territorial fish usually end in a chase (*j*), with the dominant fish pursuing.



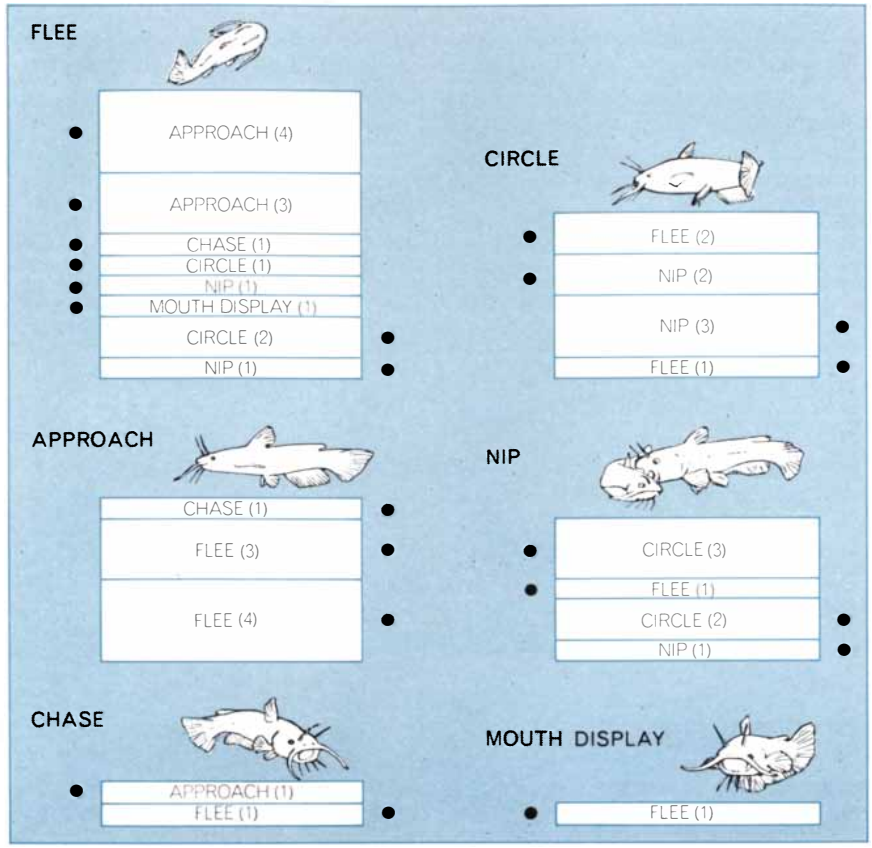


COMPLEX INTERACTIONS are characteristic of the encounters between bullhead strangers. Each of the columns in this diagram identifies one kind of action that one of the strangers frequently repeated during a prolonged encounter. The column subdivisions identify preceding or following actions by kind and frequency; the dots show whether the action preceded (*left*) or followed (*right*). Arrangement of the columns is in order of relative magnitude only; although "approach" is most frequently an initial action, temporal sequences are not represented. A simple encounter between dominant and subordinate is illustrated on the opposite page.

this chemical signal prevents interbreeding either in nature or in efforts to hybridize the two species in the laboratory.

Let us now return to the bullheads, because it is from these animals that we have gained a view of the wide extent of chemical communication among fishes and the sophistication of their chemical languages. Our helpful subjects in that inquiry have been the yellow catfish *Ictalurus natalis* and the brown catfish *Ictalurus nebulosus,* which are common residents in the small lakes and ponds of the eastern U.S. and are beloved by small boys who fish with hook and line. The bullheads may represent a pinnacle in the evolution of the chemical senses in fishes. Their organs of taste and smell are greatly extended and enlarged, and so are the regions of the brain involved in these senses, whereas their visual abilities are reduced or in some cases even absent. Our assumption that the bullheads would be ideal animals for the investigation of chemical communication has proved to be well founded.

At Michigan a neurologist who is a perceptive student of behavior, Jelle Atema, joined me in the investigation of bullhead behavior, and in preparation for controlled experiments on communications we spent months observing the social interactions of these fishes. One interesting feature of the behavior of bullheads is that they commonly establish a territory that they defend against intruders; in the natural habitat of a pond or lake the fish may occupy as its territory a hole in the bank or the space under a log or a burrow dug in the soft lake bed. In our laboratory tanks the fish similarly tended to form a territory, even if it was only a sharply defined region in the water. When a tank was occupied by two bullheads, each stayed in its own territory, turning back abruptly when it came to the border. If one of the pair was removed from the tank, the other still refrained for hours from invading the absent fish's territory. If a stranger was placed in the vacated territory, however, the resident soon crossed into that region and attacked the newcomer. On the other hand, when the stranger was removed and the former tankmate was returned, the resident again respected the border between the territories. Its performance suggested that a bullhead not only identifies but also remembers the identification of a particular individual, in this case an individual that, as experience had shown, would not contest the resident's territory and would allow it to enjoy a peaceful coexistence in the tank.



FLIGHT PREDOMINATES in this record of a subordinate bullhead's encounter with its dominant tankmate. Its most aggressive actions were a few nips and two chases. When two fish have interacted previously, their subsequent actions are limited in kind and number.

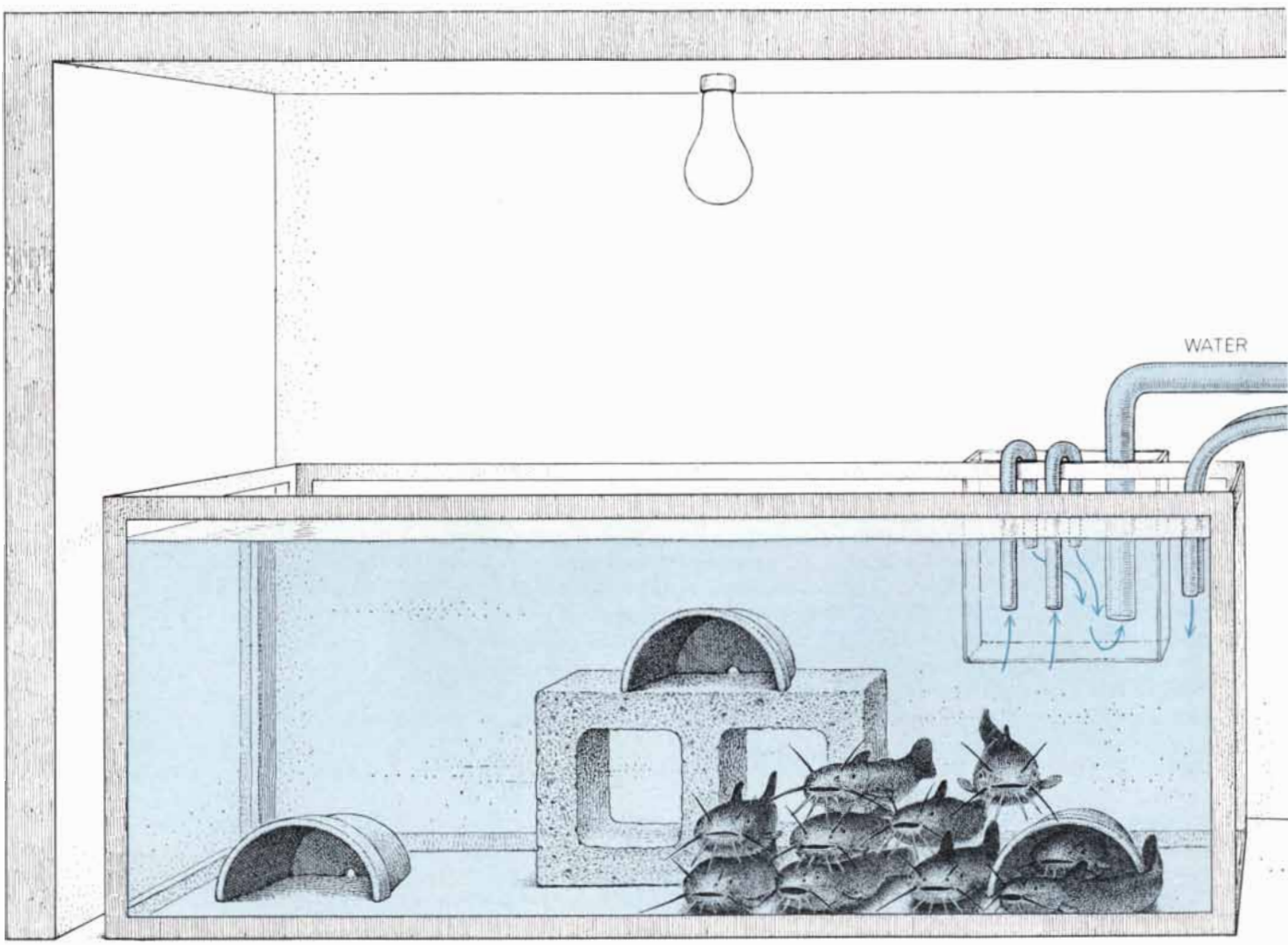
We found that except during the mating season the females as well as the males occupied individual territories. In tanks containing a number of individuals, a hierarchy usually developed; one fish, dominating the rest, would establish the largest and most protected region as its territory, and those of lower status occupied smaller and more exposed areas. A detailed analysis showed that conflicts among the bullheads took various forms depending on the relative status of the combatants. In a confrontation between two community members of equal status they merely posture in a dancelike ritual, opening their mouths in an aggressive display, making nipping gestures and alternately approaching and fleeing. In the case of a dominant member and a subordinate member the action consists mainly in flight by the subordinate and pursuit by the dominant. Only in a rivalry between two strangers does the conflict become really violent; such a fight is characterized by a variety of aggressive actions, vicious biting and occasionally death for one of the contestants. Curiously, we noted that even in nonfatal fights the loss of the fight sometimes resulted in serious consequences, apart from bodily wounds and the loss of territory, for the loser. After the battle the loser often failed to continue normal growth although it was adequately fed and housed in its own aquarium. The vanquished fish remained stunted, and after a few months it was hard to believe that the winner and the loser had been of comparable size.

Although much of the interaction between bullheads is aggressive, they exhibit cooperative behavior on occasion. When a stranger is inserted into a small community of a few fish, the dominant member allows its subordinate tankmates to swim into its territory and climb on its back for protection; after this the "boss" issues forth and engages the intruder in combat. On one occasion when a stranger swam into the boss's territory along with a subordinate tankmate of the boss, the boss evicted the stranger but allowed the tankmate to remain for a while. After the boss had defeated the stranger, however, it eventually drove

the intruding tankmate out of its shelter.

The social behavior and recognition of bullheads apparently depend very little on vision; their behavior did not change significantly when fish in our laboratory were blinded (a condition that prevails in some bullhead populations in nature). For the bullheads, chemical cues are dominant, and their memory in the recognition of such cues is phenomenal. A single example will suffice to illustrate this point. Shortly after several small bullheads had been placed in a tank it happened that a large bullhead leaped in from an adjoining tank and began to maul the little fish severely. All but two jumped out to the floor and died, so that when the intruder was removed only two survivors were left in the tank. They established separate territories at the opposite ends of the tank. To test their response to a chemical cue, we introduced some water from the tank of the bullhead that had attacked them. The two fish, disregarding territoriality, fled and hid together, returning to their own territories and shelters only after the danger signal had disappeared. Although the threatening bullhead itself did not enter their tank, for four months the two fish fled and hid every time they were exposed to water from the onetime attacker's tank. The memory of the chemical signal identifying their attacker stayed with them. They made no comparable response to water from other bullheads' tanks.

At this point in our research we began efforts to verify the existence of individual chemical "labels" in bullheads and to find the organic source of the identifying pheromones. Our first experiment was designed to test the fish's ability to discriminate between the signals from two bullhead individuals. One of the individuals represented a positive stimulus offering a food reward for the correct response; the other represented a negative stimulus, and the wrong response to it would result in an electric shock. The fish to be tested was placed in a small tank in which there was a shelter made of half a flowerpot lying on its side. A small amount of water from the aquarium of one of the two individuals to be discriminated was poured into this tank. When the water came from the "positive" subject, the test fish would receive the food reward if it rose to the tank surface, stuck its head out of the water and opened its mouth within five seconds after sensing the chemical signal. When the water was from the "negative" individual, the test fish had to retreat to its shelter within five seconds after sensing the chemical signal in order to avoid the electric shock, delivered in the tank by means of silver electrodes.



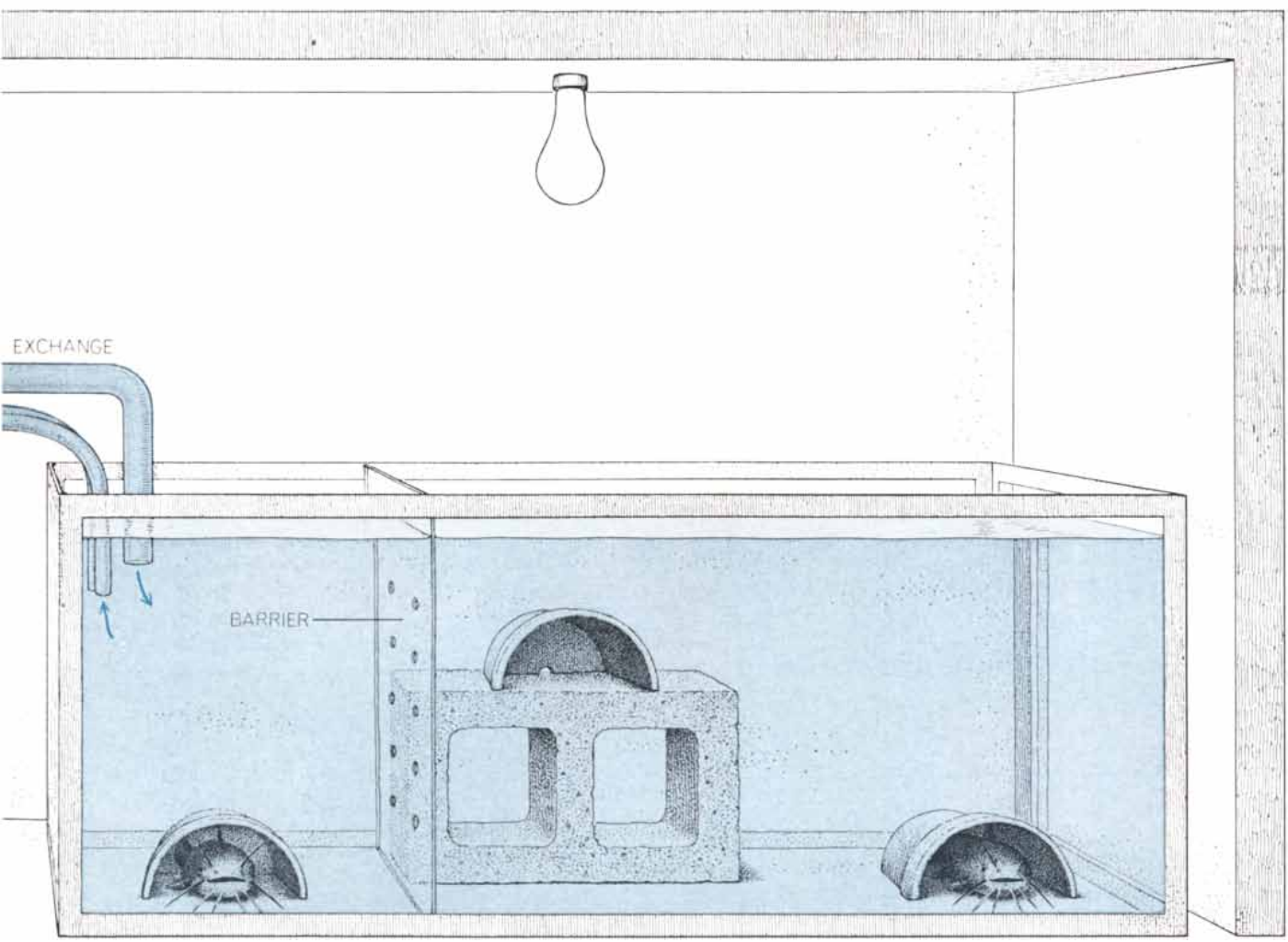
PAIR OF AQUARIUMS provided the setting for an effort to see whether or not the placid behavior of bullheads when associating in groups might depend on the secretion of an antiaggression pheromone. A communal group, 10 in number, was established in one tank (*left*); two normally aggressive bullheads, separated by a barrier, occupied the other (*right*). Water could be transferred from

The tested bullheads readily distinguished one chemical signal from the other, and after about 25 training trials they were able to respond correctly in 95 percent of the trials (totaling 937 for the 10 tested fish). All the fish retained the learned discrimination for at least three weeks without retraining. Several of the animals developed an interesting reaction to the negative stimulus. They used their five seconds of grace to attack the stimulus with hostile mouth display and quivering before darting to the shelter!

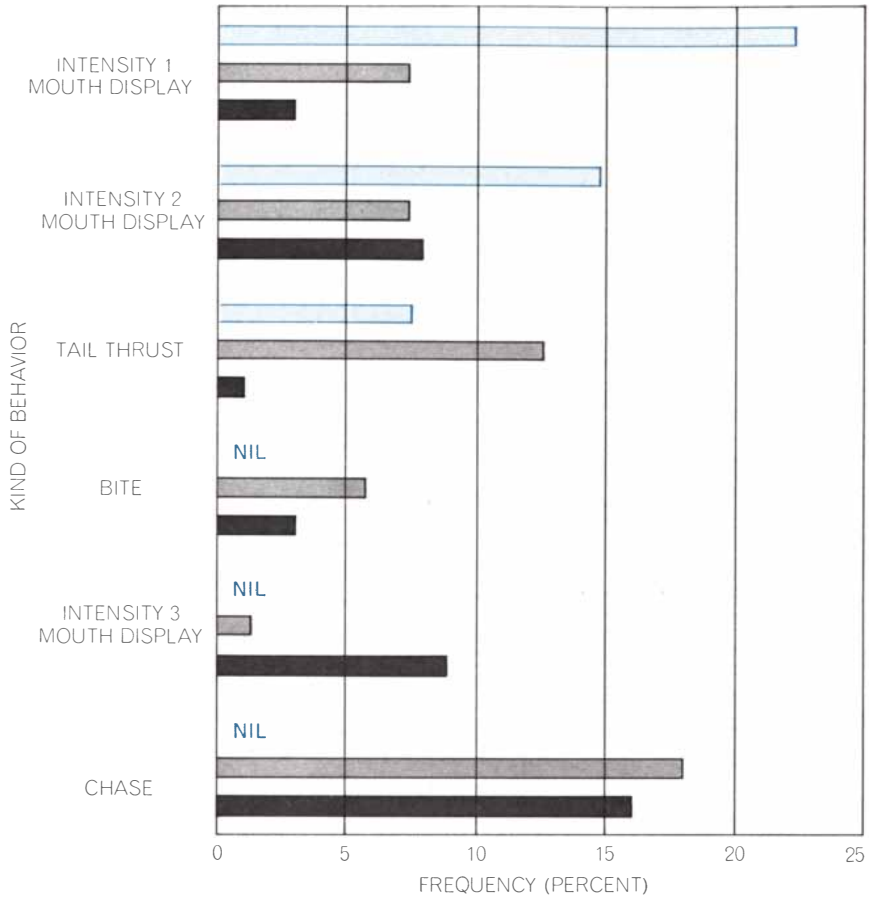
In order to determine whether the chemical signal was detected by the sense of smell or by taste we destroyed the smelling receptors in some of the animals. These animals proved to be unable to tell one signal from the other, no matter how much training they were given. Clearly chemical communication in the bullheads is delivered through the smelling sense. This supports our hypothesis that the bullhead uses two channels: the taste buds to find its way to food and the nose to receive social communications.

For further study of the importance of the sense of smell in controlling the social behavior of bullheads we set up a community consisting entirely of fish that had been deprived of their nose tissues. These fish behaved as if they were all strangers to one another. They did not form mutually respected territories, engaged in vicious mouth fights lasting up to 20 minutes, did not flee when defeated but turned and attacked the opponent again and carried on their aggressive behavior for weeks. Only after their olfactory tissues had regenerated did the fish in this tank begin to act like members of a nonbelligerent community. We found also that when a bullhead deprived of its nose was introduced into a normal community, it failed to adjust in spite of repeated defeats and showed no sign of developing recognition of the individuals in the tank or awareness of the community's social structure. It became quite evident that the communication necessary for the formation and maintenance of a stable community depends entirely on the members' sense of smell.

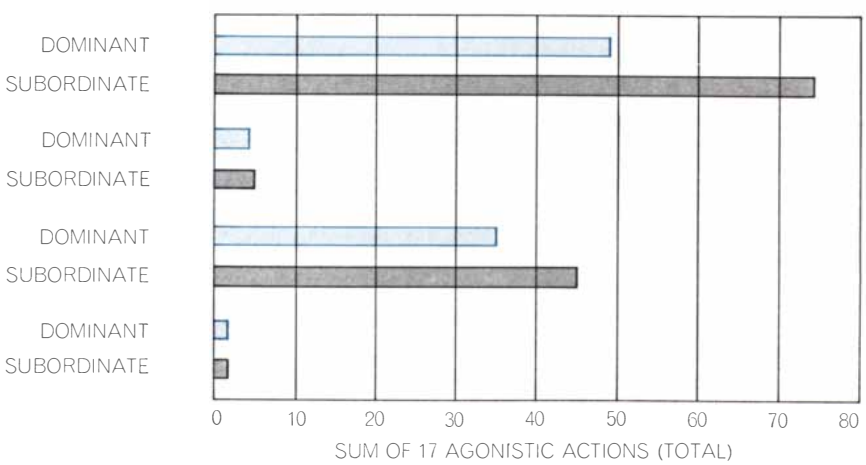
In a natural environment bullheads often form a dense community, composed of hundreds of individuals, that is based not on a hierarchy or a collection of territories but on close togetherness, with the members swimming freely and peacefully throughout the pond that houses the community. We were able to reproduce such a community in the laboratory simply by placing a large number of newly trapped bullheads in one tank. The members then spent most of their time resting in close contact with one another in a kind of "love-in." These



one tank to the other (*arrows*). Removal of the barrier incited the isolated bullheads to aggressive action; the experimenters then pumped "love-in" water from the communal tank to the aggressors' tank. Short periods of exposure failed to affect the aggressive bullheads, but after seven consecutive days agonistic behavior was substantially diminished. Brief reexposures had the same effect.



SIX AGONISTIC ACTIONS occur among bullheads with varying frequency under different living conditions. Two relatively unaggressive actions, for example, are mouth displays of the first and second level of intensity. In these categories fish in placid communities (*color*) outscore the dominant (*gray*) and subordinate (*black*) members of a territorial pair. Territorial bullheads are active, however, in other agonistic categories, such as biting and chasing; this behavior is not observed in communal groups. Territorial bullheads engage in about three times as many kinds of interaction as bullheads living in communal groups do.



EFFECT OF "LOVE-IN" PHEROMONE on two isolated bullheads is shown in this graph. Length of each bar indicates the number of agonistic incidents in any of 17 categories of behavior recorded during eight hour-long observation periods. The gray bars present the behavior of the subordinate fish and the colored bars the behavior of the dominant. At first (*top*) the fish received no water from an adjacent communal tank (*see illustration on preceding two pages*). The bars second from the top record the bullheads' actions after a seven-day exposure to the pheromone. The next bars show the result of a 24-hour respite from the pheromone and the last (*bottom*) the result of resupplying it for 24 hours more.

individuals would become aggressive only if they were removed from the dense community, isolated for several weeks and then introduced into a low-density community.

With William McLarney, a behavioral ecologist, and Mark Park, a graduate student, I looked into the possibility that the establishment of the dense, peaceful type of community might be controlled by a specific chemical factor. We first compared the typical pattern of behavior in communal groups with that characteristic of bullheads in communities of the low-density, territorial type. The communal fish undertook very few aggressive acts, indulging only in mild manifestations such as head thrusts and low-level mouth displays. We then placed two identical tanks side by side, one containing 10 communal bullheads, the other a pair of territorial bullheads, with an arrangement for pumping water from the communal tank into the territorial one. The two fish in the territorial tank (a dominant and a subordinate) would be allowed to interact aggressively (by raising a glass partition that usually kept them apart) and then water would be pumped into their tank from the communal one. If the communal fish exuded an antiaggression, "love-in" substance, the receipt of this signal might be expected to calm the aggressive fish.

Our first trial, in which the territorial fish were exposed to a suffusion of the communal water for one hour, produced no such inhibitions; in fact the fish slightly increased the intensity of most of their aggressive acts. When we gave the fish continuous repetitions of this treatment, however, at the end of the seventh day they abruptly desisted almost completely from their aggressive behavior. On coming together the two fish behaved like communal bullheads. The introduction of communal water was then suspended for a day, and within 24 hours the high level of aggression was restored. The communal water treatment was renewed, and this time not seven days but one day of exposure sufficed to suppress the aggressive behavior.

Thus it seems that the clustering of bullheads in dense aggregations does produce a concentration of pheromone that acts to inhibit aggression. The experimental results suggest that some part of the bullhead's brain may need to be primed with a certain amount of this substance before it can take effect. It is not clear what benefits are conferred on bullhead survival by this curious system of two kinds of society: territorial and communal. Perhaps the communal ag-

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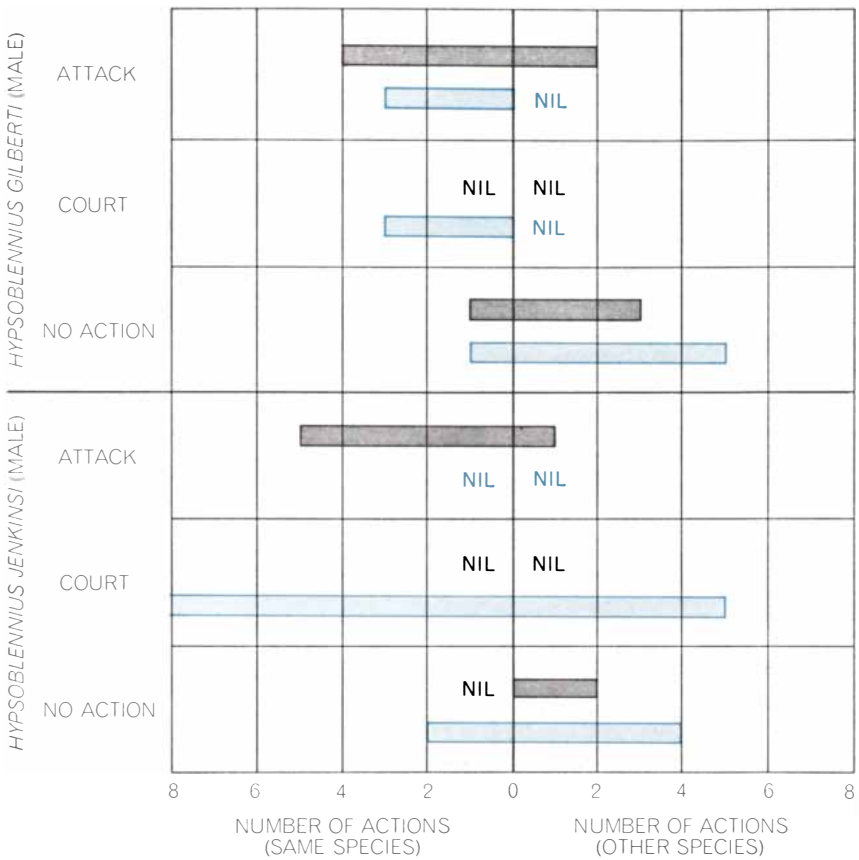
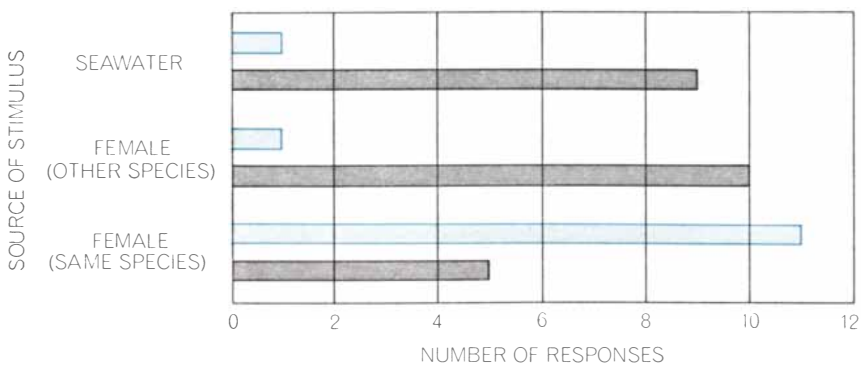
gregations provide a reserve for replenishment of the territorial populations. Field studies may throw some light on the question.

What are the sources and nature of the chemical signals—the alphabet—of the bullhead's language? A few clues have been uncovered. It turns out that the odor of the mucus on the fish's skin is sufficient to identify an individual for another bullhead of the same species. This cannot be the whole story, however, because a more intense response is evoked by the water that has bathed the fish, which suggests that other substances are involved. Perhaps the odor of secretions from the gonads serves to identify the fish's sex. The urine also may carry identifying information, although our tests of this material show that it alone does not supply enough information for recognition of an idividual. Possibly products in the urine indicating the state of stress of the fish may signal whether it is a dominant or a subordinate individual in its community.

We have done a few experiments on this question of the recognition of a bullhead's status. When a dominant fish is removed from its community, subjected to defeat by a fish we use as a "hatchet man" and then returned to the company of fish it dominated, the other fish no longer flee. Apparently the defeated fish has undergone a chemical change. In order to determine whether this alters the fish's identity as an individual or merely informs the other fish of its change in status, we applied the test to a pair, one dominant and the other subordinate, that had occupied the same tank. When the erstwhile dominant member was returned to the tank after a defeat, the originally subordinate tankmate attacked it. In this attack, however, the acts did not include those employed against a stranger (such as mouth fighting and biting) but were limited to the displays made against a known individual. In short, the attacker apparently recognized the returnee and also detected its change in status.



SEXUAL ISOLATION in the case of two species of blennies, both inhabitants of California coastal waters, is shown to depend on cues other than visual ones. The graph records the response of a male of each species to the sight of males (*gray*) and females (*color*) of the same or the opposite species, isolated in sealed jars and placed in a tank with the test subjects. *Hypsoblennius gilberti* males attacked males of both species but courted only females of their own kind. *H. jenkinsi* males, however, courted females of either species on sight.



ISOLATING PHEROMONE proved to be a secretion that is produced by a female blenny during courtship ritual. The graph shows that the number of times a male *H. jenkinsi* reacts by courting (*color*) or fails to react (*gray*) is the same when either plain water or water from a jar containing a courted female of another species is added to its tank. Intense courting occurs only when the water comes from the jar of a female of the same species.

We are a long way still from deciphering the chemical language of bullheads. It is probably complex, communicating information about the individual's species, status, sex, age or size, reproductive state, individual characteristics and perhaps even family identification. No doubt pheromones are a means of communication between parents and their young. We also have evidence that there is some chemical communication between one species and another.

David Boylan, who is working with us in a research program at the Woods Hole Oceanographic Institution, and other chemists are working to identify the chemical substances that form the languages of fishes. In the not too distant future these substances will be used in marine farming as selective attractants, artificial baits, growth stimulators, inhibitors of aggression and cannibalism and repellents to deter predators from attacking cultivated fishes. Thus they may be even more useful than the application of insect pheromones to the control of pests and diseases in agriculture.

At some companies, the assembly line isn't the only place you find interchangeable parts.

Be wary of the organization whose executive lapses too quickly into the "we're-all-little-cogs-in-the-great-big-wheel, we're-all-just-members-of-the-team" brand of thinking.

You've met the guy. If you're young and unlucky, you may have confronted him at a score of job interviews. If you're older, wiser and luckier, you may only have had to listen to him at an infrequent business lunch (where at least he could do you no permanent damage).

At best, he is a bore talking to hear himself talk. More frightening is the possibility that he believes in what he says and represents accurately the shallowness of his company's understanding of the value of *individualism.*

What's wrong with a wheel full of little cogs?

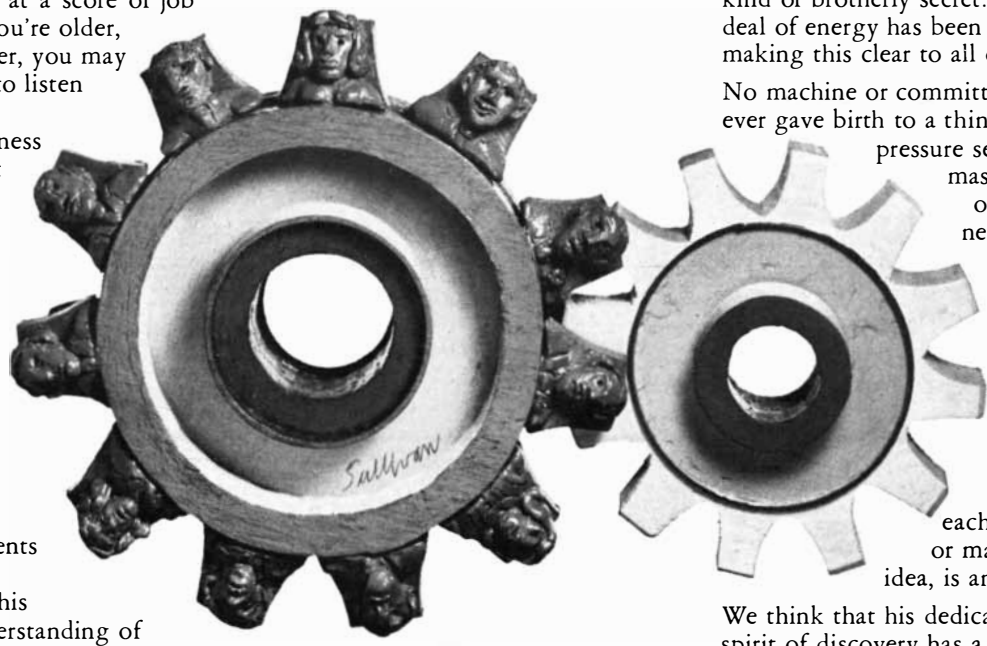
Nothing, as long as you are talking about tractors, not people. But people are not stamped out of stainless-steel, neatly interchangeable with other pieces of stainless-steel.

People think. They grow. They make mistakes and learn. They have ideas. They offer opinions. They share knowledge. They enthuse. They lead. In short, they act like *individuals.*

Would the Minnesota Vikings knock "teamwork"?

Yes. If it meant to them a blind and desperate game of follow-the-leader, as it does to so many institutions.

We think that "teamwork", even narrowly defined, leaves room for exceptional contribution on the part of exceptional members of the team without diminishing the success of the whole. We'll bet that the Vikings agree with us.



There's a catch to it.

People need the right climate. They simply will not act like individuals unless you treat them like individuals. Mostly, they won't offer opinions unless you make it clear that you are seeking opinions. They certainly aren't going to risk the possibility of making mistakes unless they know that you believe a few mistakes on the way to greatness are inevitable.

At 3M, we are committed to a belief in individual worth. And we haven't kept it locked in our hearts as a kind of brotherly secret. A good deal of energy has been devoted to making this clear to all our people.

No machine or committee at 3M ever gave birth to a thing like pressure sensitive masking tape, or an amazing new office machine that copies color in color.

At the heart of each new invention, each production or marketing idea, is an *individual.*

We think that his dedication and spirit of discovery has a direct relation to our dedication to the principle of individual worth.

3M is a continuing success story. Because everybody is *somebody* at 3M.

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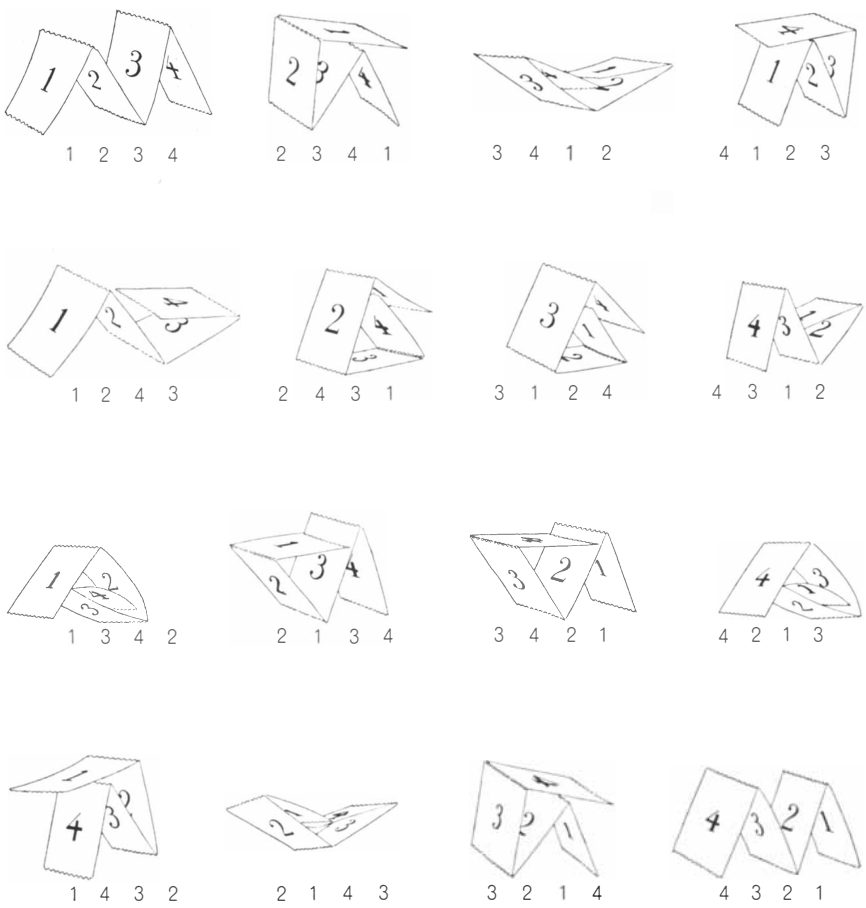
MATHEMATICAL GAMES

The combinatorial richness of folding a piece of paper

by Martin Gardner

One of the most unusual and frustrating unsolved problems in modern combinatorial theory, proposed many years ago by Stanislaw M. Ulam, is the problem of determining the number of different ways to fold a rectangular "map." The map is precreased along vertical and horizontal lines to form a matrix of identical rectangles. The folds are confined to the creases, and the final result must be a packet with any rectangle on top and all the others under it. Since there are various ways to define what is meant by a "different" fold, we make the definition precise by assuming that the cells of the unfolded map are numbered consecutively, left to right and top to bottom. We wish to know how many permutations of these n cells, reading from the top of the packet down, can be achieved by folding. Cells are numbered the same on both sides, so that it does not matter which side of a cell is "up" in the final packet. Either end of the packet can be its "top," and as a result every fold will produce two permutations, one the reverse of the other. The shape of each rectangle is irrelevant because no fold can rotate a cell 90 degrees. We can therefore assume without altering the problem that all the cells are identical squares.



The 16 ways to fold a four-stamp strip

The simplest case is the 1-by-n rectangle, or a single strip of n squares. It is often referred to as the problem of folding a strip of stamps along their perforated edges until all the stamps are under one stamp. Even this special case is still unsolved in the sense that no nonrecursive formula has been found for the number of possible permutations of n stamps. Recursive procedures (procedures that allow calculating the number of folds for n stamps provided that the number for $n-1$ stamps is known) are nonetheless known. The total number of permutations of n objects is $n!$ [that is, factorial n, or $n \times (n-1) \times (n-2) \ldots \times 1$]. All $n!$ permutations can be folded with a strip of two or three stamps, but for four stamps only 16 of the $4! = 24$ permutations are obtainable [*see illustration on this page*]. For five stamps the number of folds jumps to 50 and for six stamps it is 144. John E. Koehler wrote a computer program, reported in a 1968 paper, with which he went as high as $n = 16$, for which 16,861,984 folds are possible. W. F. Lunnon, in another 1968 paper, carried his results to $n = 24$, but he says there may have been computer errors above $n = 21$.

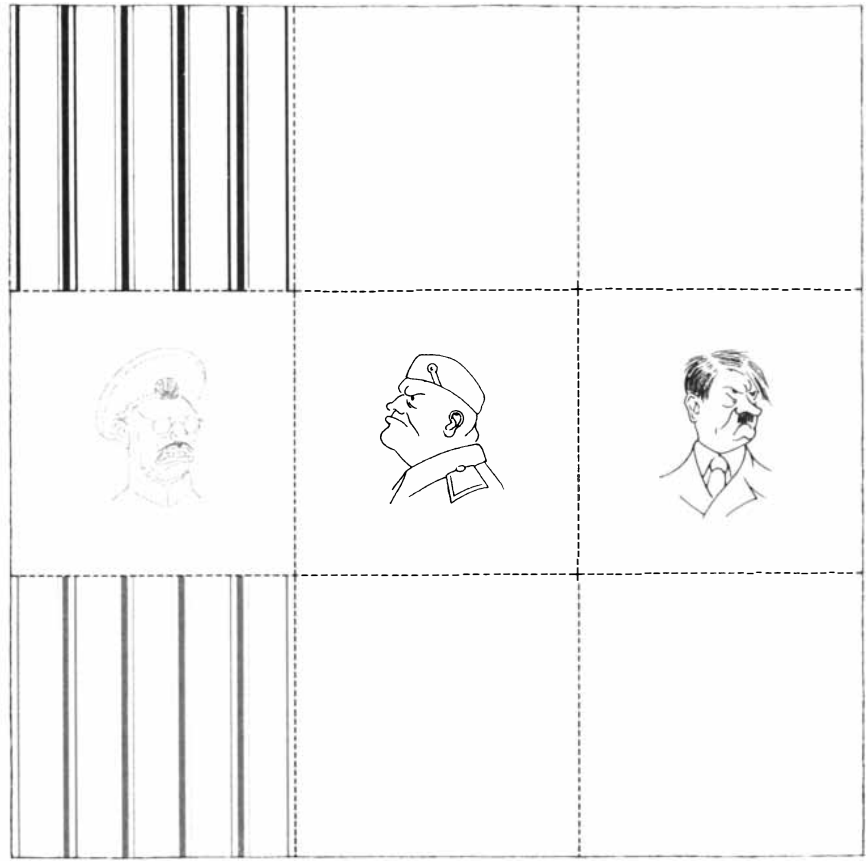
The simplest rectangle that is not a strip is the trivial 2-by-2 square. It is easy to find that only eight of the $4! = 24$ permutations can be folded, half of which (as explained above) are reversals of the other half. The 2-by-3 rectangle is no longer trivial, because now it becomes possible to tuck one or more cells into open pockets. This greatly confuses matters. As far as I know, nothing has been published on the nonstrip rectangles. I was able to fold 60 of the $6! = 720$ permutations (10 folds for each cell on top), but it is possible I missed a few.

An amusing pastime is to find six-letter words that can be put on the 2-by-3 map (lettering from left to right and from the top down) so that the map can be folded into a packet that spells, from the top down, an anagram of the original word. Each cell should be labeled the same on both sides to make it easier to identify in the packet. For example, it is not hard to fold ILL-FED to spell FILLED and SQUIRE to spell RISQUE. On the other hand, OSBERG (an anagram for the last name of the Argentine writer Jorge Luis Borges that appears on page 361 of Vladimir Nabokov's novel *Ada*) cannot be folded to BORGES, nor can BORGES be folded to OSBERG. Can the reader give a simple proof of both impossibilities?

The 2-by-4 rectangle is the basis of

two map-fold puzzles by Henry Ernest Dudeney (see page 130 of his *536 Puzzles & Curious Problems,* Scribner's, 1967). Dudeney asserts there are 40 ways to fold this rectangle into a packet with cell No. 1 on top, and although he speaks tantalizingly of a "little law" he discovered for identifying certain possible folds, he offers no hint as to its nature. I have no notion how many of the $8! = 40{,}320$ permutations can be folded.

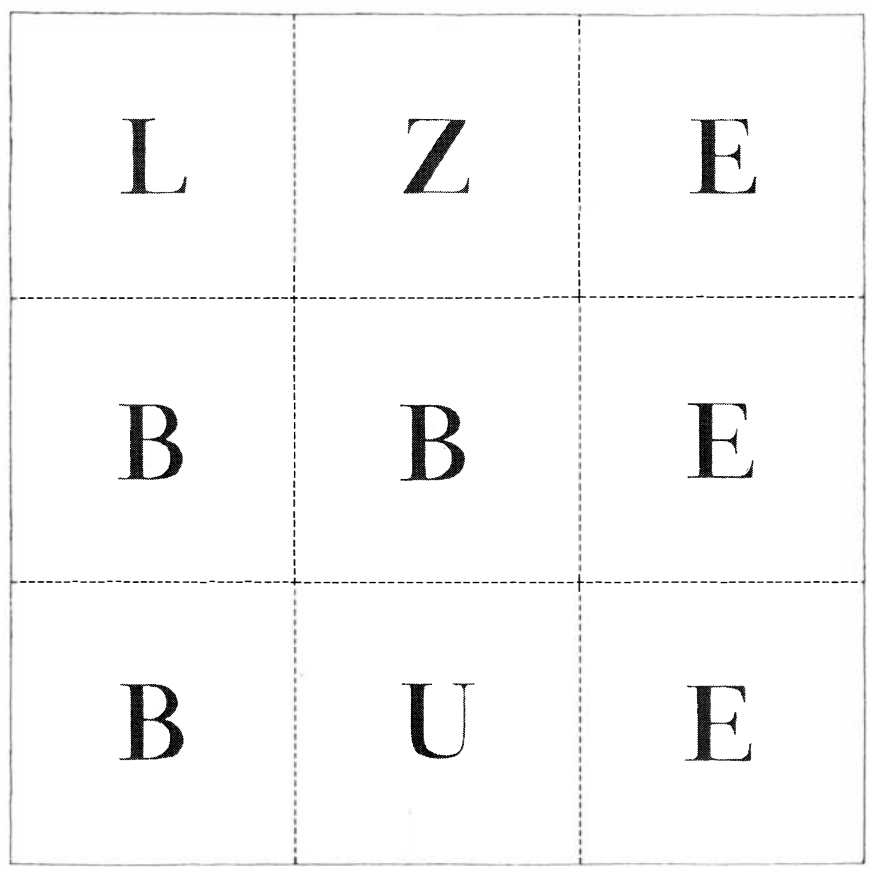
When one considers the 3-by-3, the smallest nontrivial square, the problem becomes fantastically complex. As far as I know, the number of possible folds (of the $9! = 362{,}880$ permutations) has not been calculated, although many paper-fold puzzles have exploited this square. One was an advertising premium, printed in 1942 by a company in Mt. Vernon, N.Y., that is diagrammed in the top illustration at the right. On one side of the paper there are the faces of Mussolini and Hitler. On the back of the remaining cell of the same row there is the face of Tojo, the wartime prime minister of Japan. Above this cell there is a prison window with open spaces die-cut between two bars; below the Tojo cell a similar window appears on the back of the cell, as indicated by the dotted lines. The problem is to fold the square into a packet so that at each end two of the faces appear behind the bars; that is, so that on each side of the packet the top cell bears a picture of a window and directly under it a face shows through the open slots between the bars. The fold is not difficult, but it does require a final tuck.



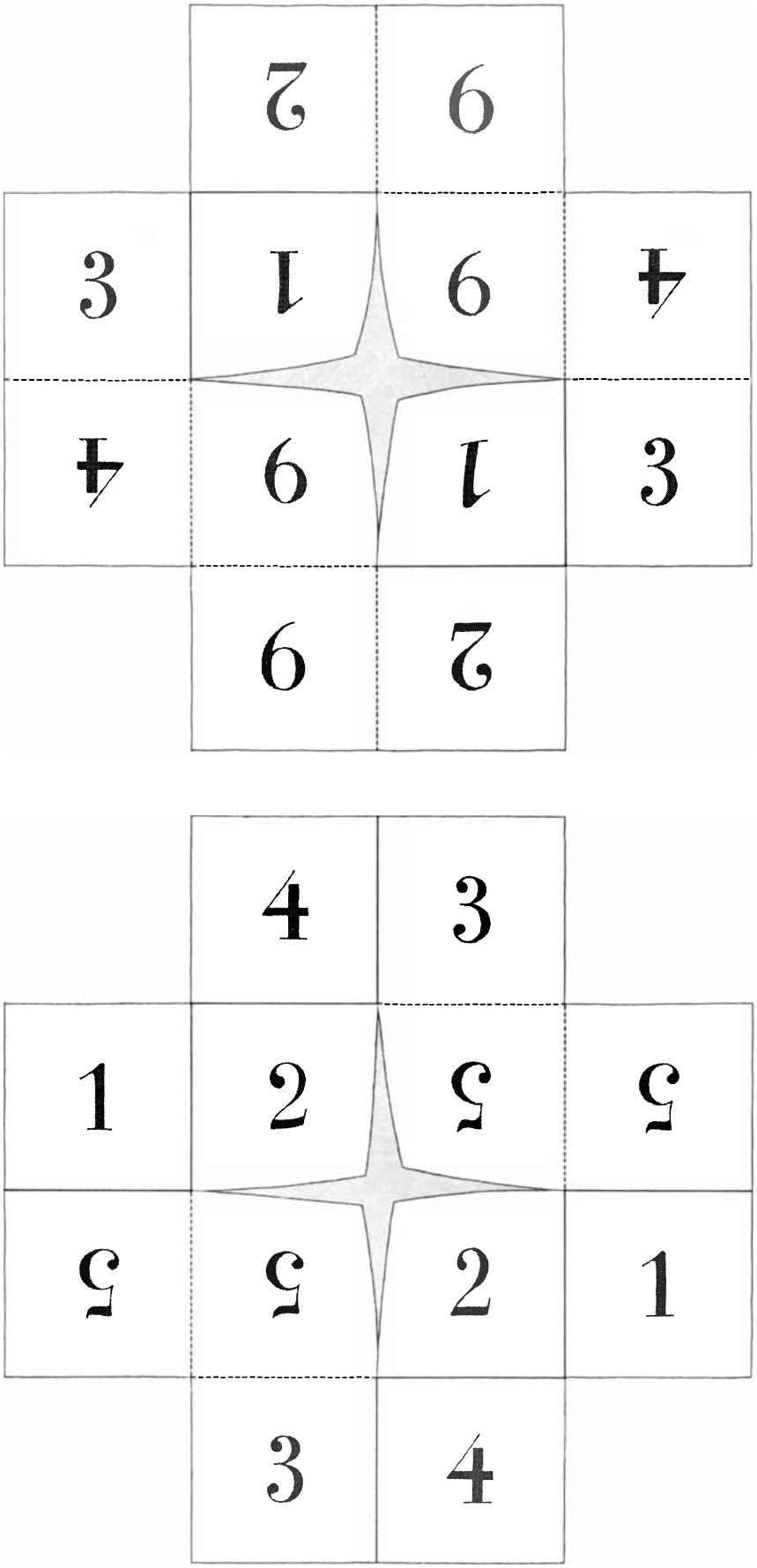
A map-fold problem from World War II

A much tougher puzzle using a square of the same size is the creation of Robert Edward Neale, a Protestant minister, professor of psychiatry and religion at the Union Theological Seminary and the author of the influential book *In Praise of Play* (Harper & Row, 1969). Neale is a man of many avocations. One of them is origami, the Oriental art of paper folding, a field in which he is recognized as one of the country's most creative experts. Magic is another of Neale's side interests; his famous trick of the bunny in the top hat, done with a folded dollar bill, is a favorite among magicians. The hat is held upside down. When its sides are squeezed, a rabbit's head pops up. (The interested reader can obtain *Bunny Bill,* a manuscript describing the fold, from Magic, Inc., 5082 North Lincoln Avenue, Chicago, Ill. 60625, for $1 postpaid. The fold is far from simple, by the way.)

The bottom illustration at the right



Robert Edward Neale's Beelzebub puzzle



Front (top) *and back* (bottom) *of the unfolded tetraflexagon*

shows Neale's hitherto unpublished Beelzebub puzzle. Start by cutting a square from a sheet of paper or thin cardboard, crease it to make nine cells, then letter the cells (the same letter on opposite sides of each cell) as indicated. First try to fold the square into a packet that spells (from the top down) these eight pseudonyms of the fallen angel who, in Milton's *Paradise Lost*, is second in rank to Satan himself: Bel Zeebub, Bub Blezee, Ube Blezbe, Bub Zelbee, Bub Beelze, Zee Bubble, Buz Lebeeb, Zel Beebub. If you can master these names, you are ready to tackle the really fiendish one: Beelzebub, the true name of "the prince of the devils" (Matthew 12:24). Its extremely difficult fold will be explained next month. No one who succeeds in folding all nine names will wonder why the general map-folding problem is still unsolved.

Neale has invented a variety of remarkable paper-fold puzzles, but there is space for only two more. One is in effect a nonrectangular "map" with a crosscut at the center [*see illustration at left*]. The numbers may represent six colors: all the 1-cells are one color, the 2-cells a second color and so on. Here opposite sides of each cell are different. After numbering or coloring as shown at the top in the illustration, turn the sheet over (turn it *sideways,* exchanging left and right sides) and then number or color the back as shown at the bottom. The sheet must now be folded to form a curious species of tetraflexagon. (Tetraflexagons were the topic of an earlier article in this department. The article is reprinted in *The 2nd Scientific American Book of Mathematical Puzzles & Diversions.*)

To fold the tetraflexagon, position the sheet as shown at the top in the illustration. (It helps if you first press the creases so that the solid lines are what origamians call "mountain folds" and the dotted lines are "valley folds.") Reach underneath and seize from below the two free corners of the 1-cells, holding the corner of the upper cell between the tip of your left thumb and index finger and the corner of the lower cell between the tip of your right thumb and finger. A beautiful maneuver can now be executed, one that is easy to do when you get the knack even though it is difficult to describe. Pull the corners simultaneously down and away from each other, turning each 1-cell over so that it becomes a 5-cell as you look down at the sheet. The remaining cells will come together to form two open-top boxes with a 6-cell at the bottom

Or, for that matter, is Los Angeles? Or Chicago? Or Philadelphia? Or Dallas?

Or any other city groping its way to an uninhabitable anachronism.

A curious situation has developed in America. Eighty per cent of the people in this country live on less than ten per cent of the land area.

There used to be a good reason for this.

At the time of the industrial revolution, we congregated in cities because that's where the sources of energy were. Coal. Water. Electricity.

And our communications network was so limited that we had to be in close proximity to each other for business and social purposes.

No more.

There are no longer any good reasons to continue this hopelessly outmoded life style.

With the advent of the whole spectrum of new communications available to us (wide-band communications, laser beams), we will have the opportunity to live in significantly less dense population centers.

This is no idle prophecy.

The concept is quite realistic and well within the bounds of engineering capabilities which we already have.

Not only do we have the tools to provide the means for new styles in human settlements, but also to rebuild, in a sociological sense, the crowded inner core of our major cities.

The combination of international satellites and cable will provide the means of bringing individuals all the information they need or want without interference or control.

And without the need to be in any specific place.

(Think for a moment about the Apollo 11 moon landing in July, 1969. 500 million people around the world saw, via television, *precisely the same thing at the same time.* Being in New York or Los Angeles held no advantage over being in Keokuk or Harrisburg.)

Historically, we've been preoccupied with moving people and objects. Thus, our intricate network of highways and railroads and airlines — all of which have become enormously inefficient (not inherently, but in application).

The future will see us moving *information,* not, by necessity, people and things.

Your home will be the absolute center of your life.

You will work from home, shop from home, "visit" with family and friends from home, receive in your home any intellectual or cultural achievement known to man.

Fantastic, yes. Fantasy, no.

It is quite within reason to expect these changes by the 1980's.

If we want them.

If we want to change. If we want a better life for ourselves.

Technology has advanced to such an extent, that man is now, literally, capable of changing his world.

Yet, today, a certain gap has developed between the potential of technology and its use by mankind.

There is an obvious contradiction in a method which can land a man on the moon, yet tolerates, perhaps even accepts as inevitable, poverty and ignorance here on earth.

There is a contradiction in a method which affords the best of everything for some, and next to nothing for others.

So we must, in a sense, catch up with the technological potential and apply it for the benefit of all mankind.

All we need sacrifice are the antiquated work practices and our anachronistic traditions.

At RCA, through research and product development, we are committed to closing the technology gap and cancelling the contradictions.

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If you are interested in a comprehensive index of over 1100 technical papers published by RCA scientists and engineers during 1969, let us know.

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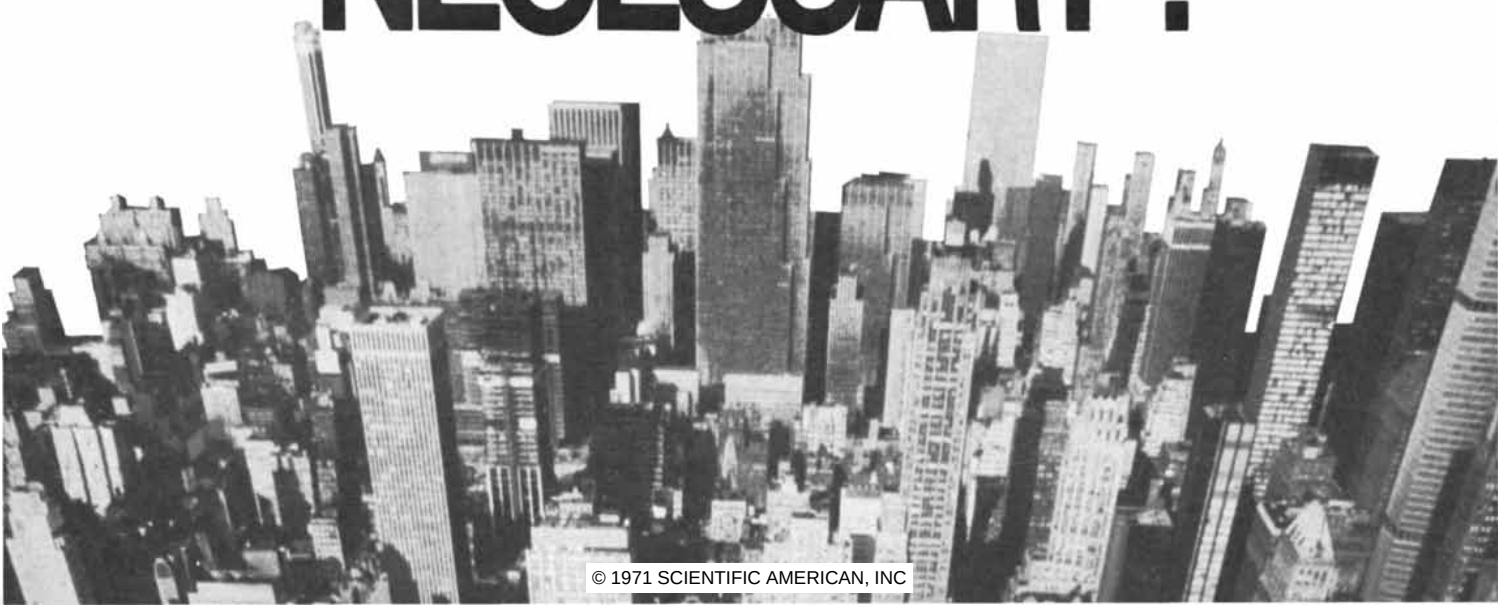
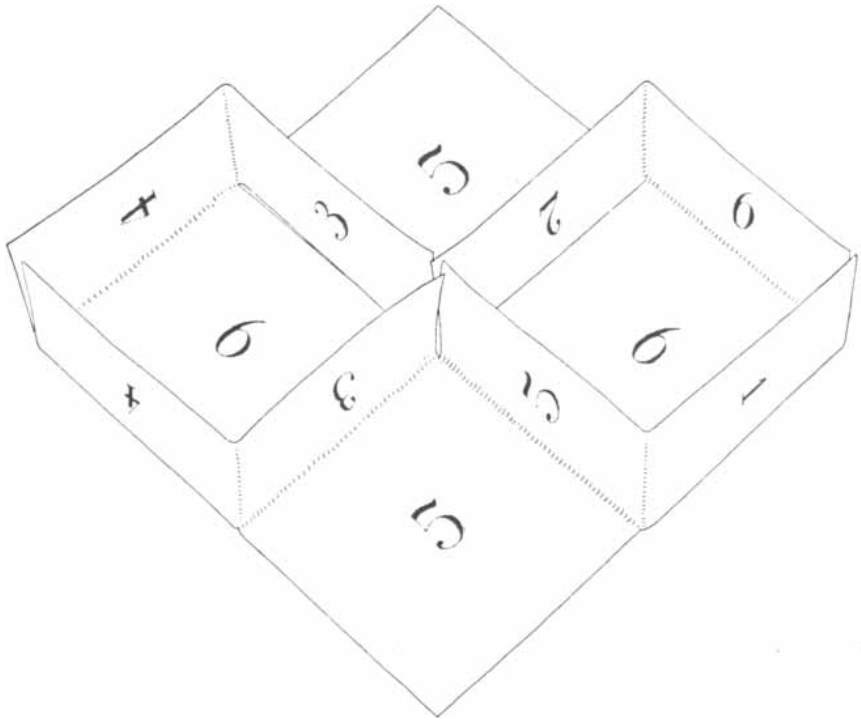
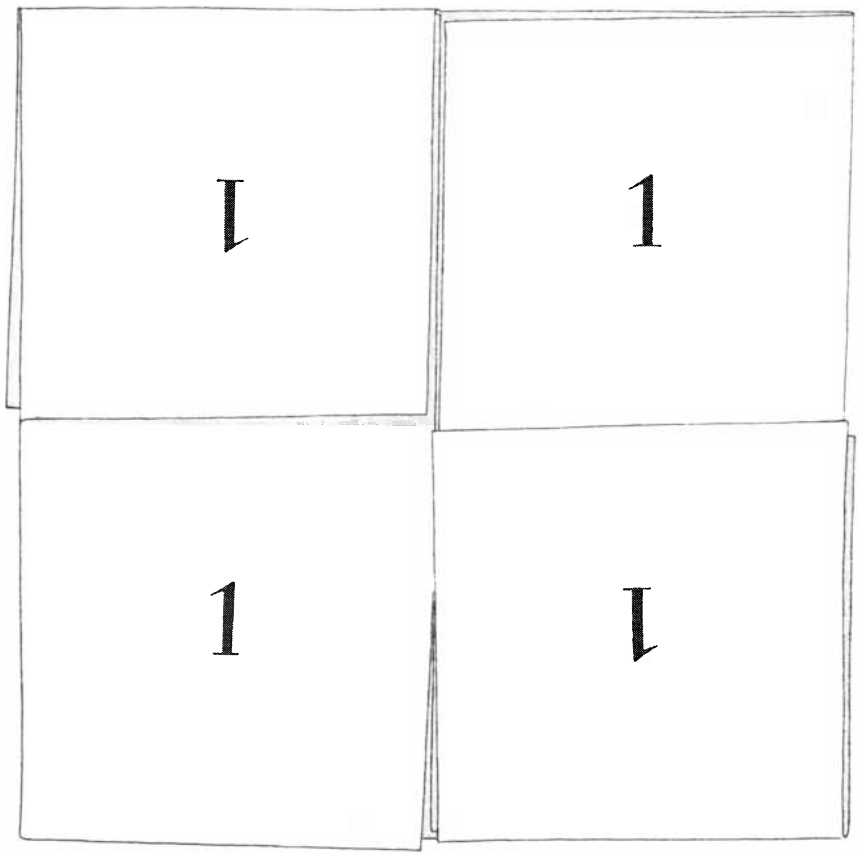
IS NEW YORK REALLY NECESSARY?





First step in folding the tetraflexagon



Final step in folding the tetraflexagon

of each box [*see top illustration at left*].

Shift your grip to the two inside corners of the 5-cells—corners diagonally opposite the corners you were holding. Push down on these corners, at the same time pulling them apart. The boxes will collapse so that the sheet becomes a flat 2-by-2 tetraflexagon with four 1-cells on top and four 2-cells on the underside [*see bottom illustration at left*]. If the collapsing is not properly done, you will find a 4-cell in place of a 1-cell, and/or a 3-cell in place of a 2-cell. In either case simply tuck the wrong square out of sight, replacing it with the correct one.

The tetraflexagon is flexed by folding it in half (the two sides going back), then opening it at the center crease to discover a new "face," all of whose cells have the same number (or color). It is easy to flex and find faces 1, 2, 3 and 4. It is not so easy to find faces 5 and 6.

One of Neale's most elegant puzzles is his "Sheep and Goats," which begins with a strip of four squares and a tab for later gluing [*see top illustration on page 116*]. Precrease the sheet (folding it both ways) along all dotted lines. Then color half of each square [*dark gray in illustration*] black—on both sides, as if the ink had soaked right through the paper.

The strip is folded as shown in steps *a, b, c* and *d*. The first fold is back and down. The next three folds are valley folds, first to the right, then up, then left. After the last fold slide the tab *under* the double-leaved black triangle at the top left of the square. Glue the tab to the bottom leaf of the triangle. You should now have a square with four black and four white triangles on each side. These are the sheep and goats.

The problem is: By folding only along precreased lines, change the paper to a square of the same size that is all white on one side and all black on the other. In other words, separate the sheep from the goats. It is not easy, but it is a delight to make the moves rapidly once you master the steps—which I shall diagram next month, along with the answer to the tetraflexagon puzzle. (To make the manipulations smoother, it is a good plan to trim a tiny sliver from all single edges after the square has been folded and glued.)

Anyone interested in learning some of Neale's more traditional origami figures will find six of his best (including his Thurber dog) in Samuel Randlett's *The Best of Origami* (E. P. Dutton, 1963). Some of his dollar-bill folds (including the jumping frog) are in *Folding Money:*

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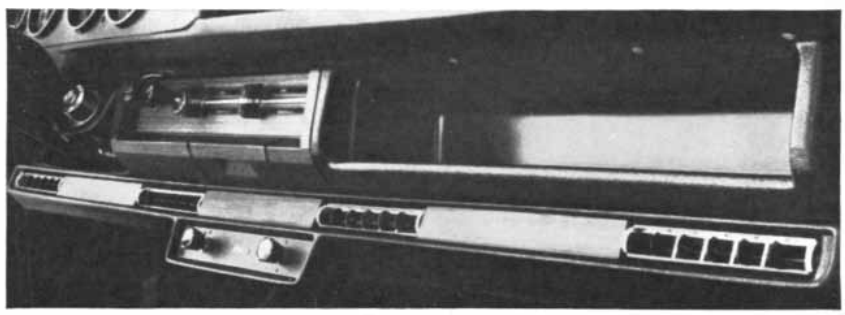
After all that, who'd be content to make do with some ugly bolt-on air conditioner? Not us. A brand-new unit was designed just for our Simca. It has four adjustable outlets, a three-speed fan, enough power to keep an Eskimo happy; and as you see, it even looks good.

Separately, our Simca and our air conditioner are tops in their class. Together for only $2,212, they're in a class by themselves.

And if you don't believe us, believe the experts. We gave Simca to some of the nation's top automotive magazines to get their reactions. Send in the coupon. We'll send you unedited reprints of the road test articles as they appeared in the actual magazines.

How's that for moxie?

Almost as good as pricing an air conditioned car at $2,212.



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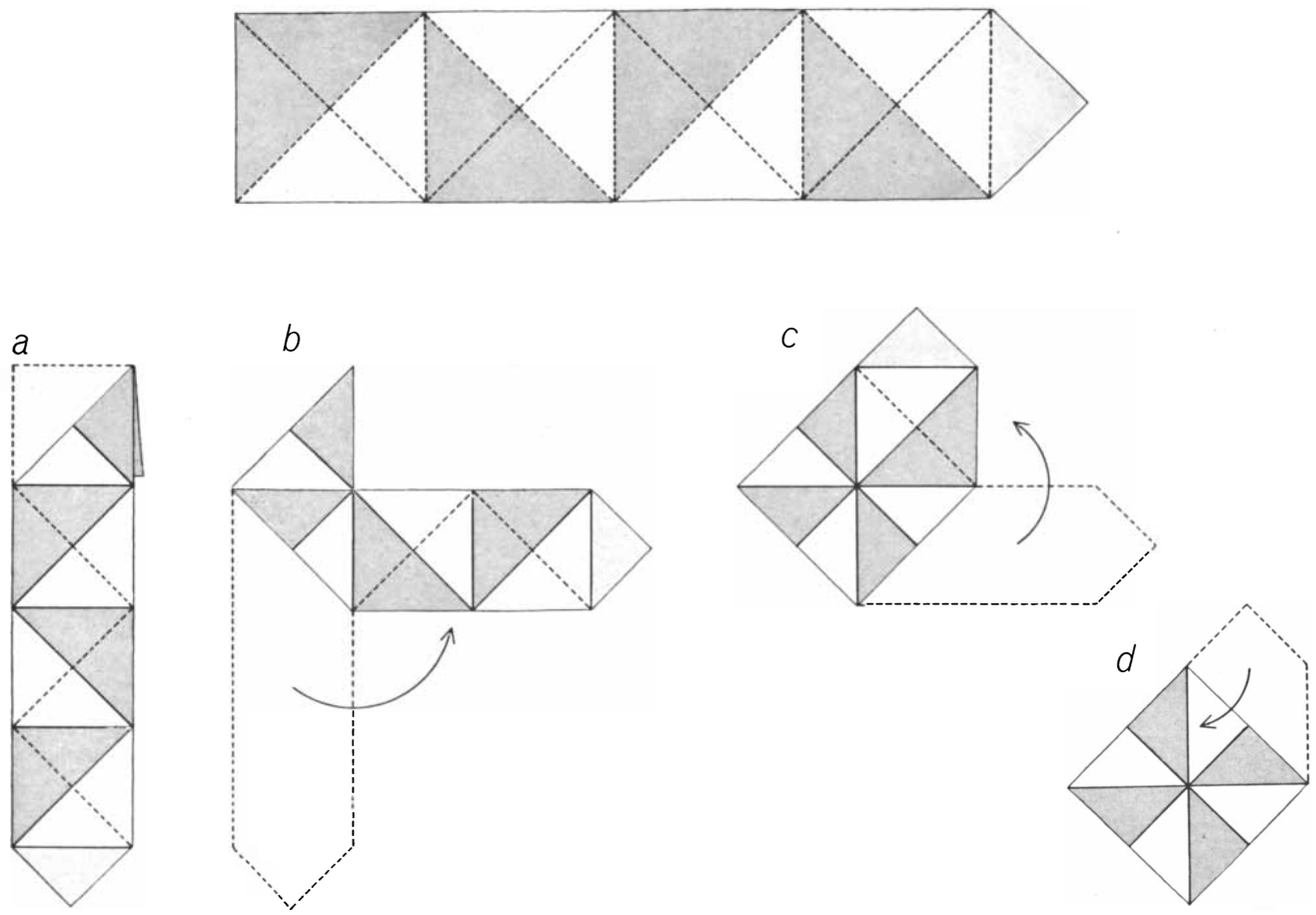
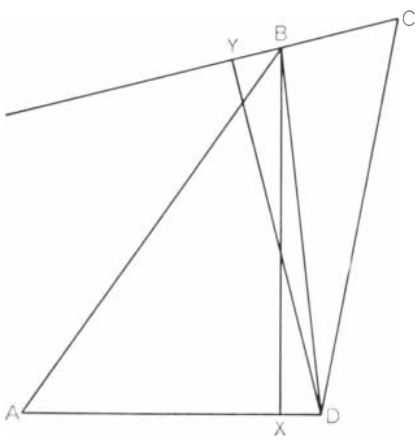


Neale's "Sheep and Goats" problem

Volume II, edited by Randlett (Magic, Inc., 1968).

The errors in last month's fallacious geometric proofs are briefly explained as follows:

Theorem 1. An obtuse angle is sometimes equal to a right angle. The mistake lies in the location of point *K*. When the figure is accurately drawn, *K* is so far below line *DC* that, when *G* and *K* are joined, the line falls entirely outside the original square *ABCD*. This renders the proof totally inapplicable.



Quadrilateral-theorem counterexample

Theorem 2. Every triangle is isosceles. Again the error is one of construction. *F* is always outside the triangle and at a point such that, when perpendiculars are drawn from *F* to sides *AB* and *AC*, one perpendicular will intersect one side of the triangle but the other will intersect an extension of the other side. A detailed analysis of this fallacy can be found in Eugene P. Northrop's *Riddles in Mathematics* (1944), Chapter 6.

Theorem 3. If a quadrilateral ABCD *has angle* A *equal to angle* C, *and* AB *equals* CD, *the quadrilateral is a parallelogram.* The proof is correct if *X* and *Y* are each on a side of the quadrilateral or if both *X* and *Y* are on projections of the sides. It fails if one is on a side and the other is on an extension of a side, as shown in the illustration at the left. This figure meets the theorem's conditions but obviously is not a parallelogram.

Theorem 4. Pi equals 2. It is true that as the semicircles are made smaller their radii approach zero as a limit and therefore the wavy line can be made as close to the diameter of the large circle as one pleases. At no step, however, do the semicircles alter their *shape*. Since they always remain semicircles, no matter how small, their total length always remains pi. The fallacy is an excellent example of the fact that the elements of a converging infinite series may retain properties quite distinct from those of the limit itself.

Theorem 5. Euclid's parallel postulate can be proved by Euclid's other axioms. The proof is valid in showing that one line can be constructed through *C* that is parallel to *AB*, but it fails to prove that there is only one such parallel. There are many other methods of constructing a parallel line through *C;* the proof does not guarantee that all these parallels are the *same* line. Indeed, in hyperbolic non-Euclidean geometry an infinity of such parallels can be drawn through *C*, a possibility that can be excluded only by adopting Euclid's fifth postulate or one equivalent to it. Elliptic non-Euclidean geometry, in which *no* parallel can be drawn through *C*, is made possible by discarding, along with the fifth postulate, certain other Euclidean assumptions.

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THE AMATEUR SCIENTIST

Schlieren photography is used to study the flow of air around small objects

Conducted by C. L. Stong

Orville Wright once remarked: "How easy it would be to improve the airplane if only we could see the splash!" Several schemes were later devised for making the flow of air visible, as the bow wave of a ship is. An early technique consisted in attaching bits of yarn to an aircraft at strategic points. The yarn served, as wind vanes do, to indicate the direction of the flow. Another useful scheme called for injecting thin trails of smoke into the airstream of a wind tunnel containing a model of the aircraft. Pressures developed on the model by the moving air could be deduced by observing the displacement of the smoke.

A similar technique involves the substitution of water for air. A sheet of water (analogous to a stream of air) flows down the upper surface of an inclined pane of glass from a trough at the upper edge of the pane. Trails of dye are injected into the water at uniform intervals across the upper edge to form a grid of straight lines. A cross section of the model to be investigated is cemented to the center of the pane and acts as an obstruction that diverts the trails of dye. Forces acting on the model can be computed from the resulting distortion of the grid by taking account of appropriate scale factors. All these stratagems, however, are useful only at rather low air speeds.

High-velocity effects are now routinely investigated by means of schlieren photography. This approach is based on an optical effect first described in the 19th century by the French physicist Jean Foucault and utilized in 1864 by the German physicist August Töpler to make differences in the density of air currents visible. In its simplest form the schlieren apparatus consists of a light source, two lenses, a pair of knife-edges and a sheet of photosensitive film.

Light from the lamp is focused by a small lens on one of the knife-edges. That edge is adjusted to the position where half of the rays are intercepted. The unobstructed rays proceed as a diverging cone to the second lens. That lens bends the rays back into a converging cone that comes to a focus on the second knife-edge, which is adjusted to the position where half of the remaining rays are intercepted. The unobstructed rays impinge on the film, which is uniformly lighted if the air between the first knife-edge and the second lens is of uniform density.

Variations in density bend the rays by refraction, with the result that the amount of light reaching the film is altered. Some rays that initially proceeded to the film are bent in the direction of the second knife-edge, where they are intercepted. The film darkens in these regions. Conversely, other rays that were originally intercepted may be bent clear of the obstruction. The film brightens in these regions. Patterns of light and shade thus appear on the film and portray variations in density. In effect the device enables the experimenter to photograph Wright's aerodynamic "splash."

An experimenter who has specialized in schlieren photography for several years is Gary S. Settles, who is an undergraduate student at the University of Tennessee. He has used the technique to investigate the flow of air around small models in a supersonic wind tunnel. Settles describes his most recent experiments as follows:

"The schlieren system is a fascinating analytical device, but it is sensitive to the quality of its optical parts, as Foucault observed. Optical defects bend light rays just as air currents do. The defects appear on the film as patterns of light and shade. Moreover, the second schlieren lens must have a substantial diameter. The column of air that can be observed can be no larger than the diameter of this lens.

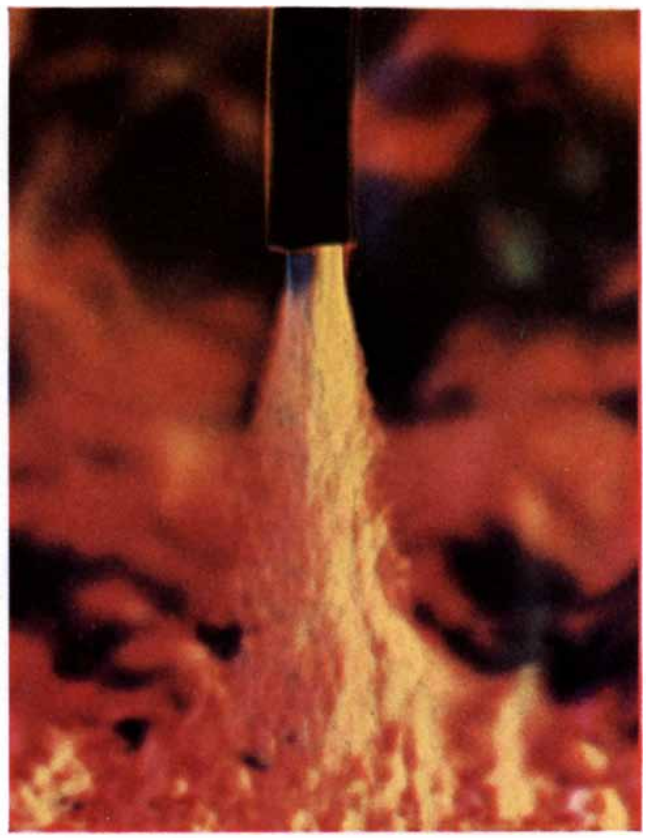
"Even small lenses of the required optical quality are costly. For this reason schlieren systems of substantial size usually employ parabolic mirrors to focus the light. Inexpensive mirrors of excellent optical quality can be made at home by the techniques described in *Amateur Telescope Making: Book One,* edited by Albert G. Ingalls (Scientific American, Inc., 1970). The substitution of a mirror for the second lens of the schlieren system requires that the light be directed toward the reflecting surface at an angle with respect to the optical axis of the mirror. The rays are reflected at an equal but opposite angle to the other side of the optical axis, where they can be observed.

"The angular reflection introduces a particularly undesirable form of optical distortion known as coma. A point source of light that is subjected to this form of distortion comes to focus as a small comet shape. Coma can be eliminated by the use of a twin mirror. Light from the source falls on the first mirror from one side and is reflected to the second mirror, proceeding from there to the film on the opposite side. The optical path is folded in the form of the letter Z.

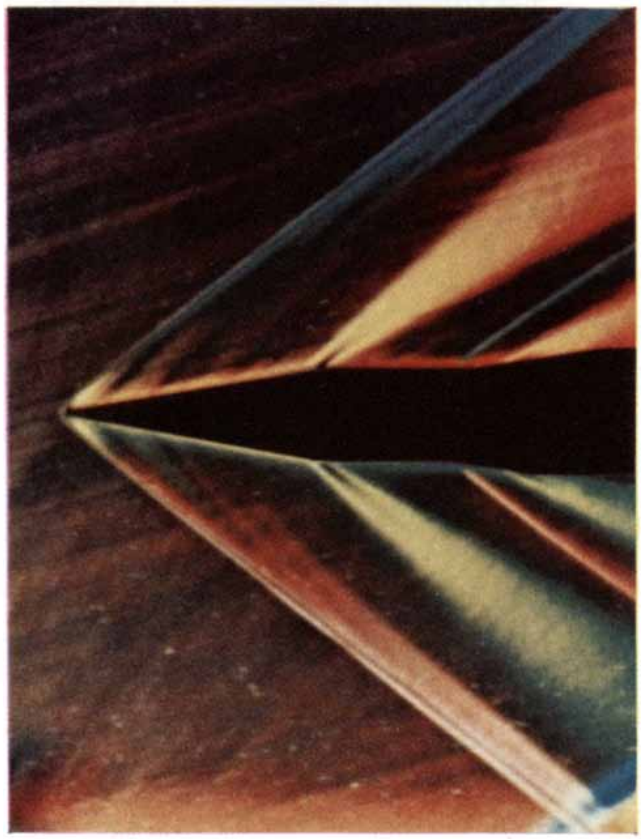
"Reflection from the first mirror introduces coma. Reflection from the second mirror cancels the distortion. Light between the two mirrors is transmitted as parallel rays. This region of the optical path is sensitive to differences in the density of air currents. It serves as the test section of the apparatus [*see top illustration on page 120*].

"The simple schlieren system yields a black-and-white image of air currents that depicts variations of density in only one direction: at a right angle with respect to the knife-edge. Usually the experimenter is interested in density gradients, or variations, in all directions, particularly in the investigation of supersonic flow. It is possible to provide the system with more than one knife-edge and to use slits in the form of a square or a circle. These expedients do not greatly increase the useful information recorded by the film, however, because the individual contribution of each slit

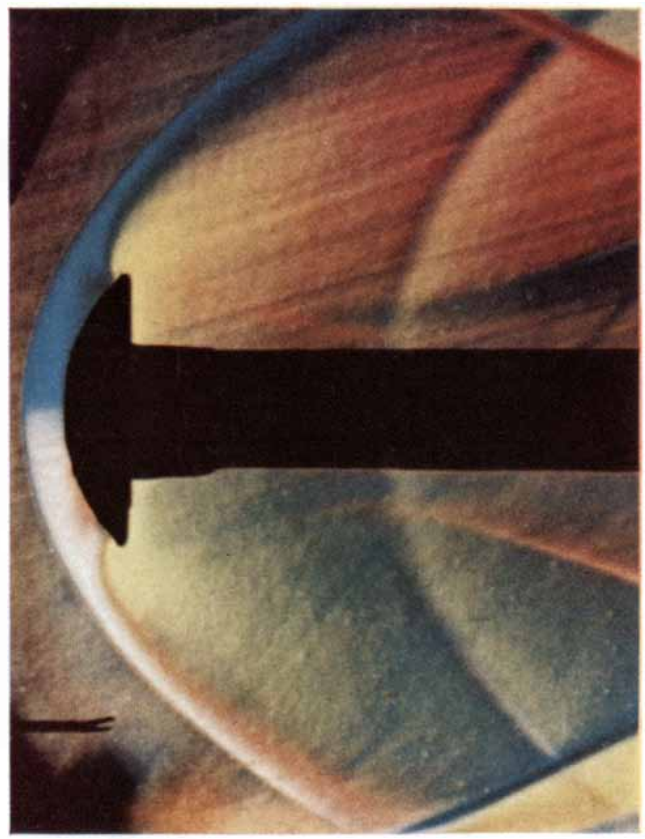
Air currents rising from hand



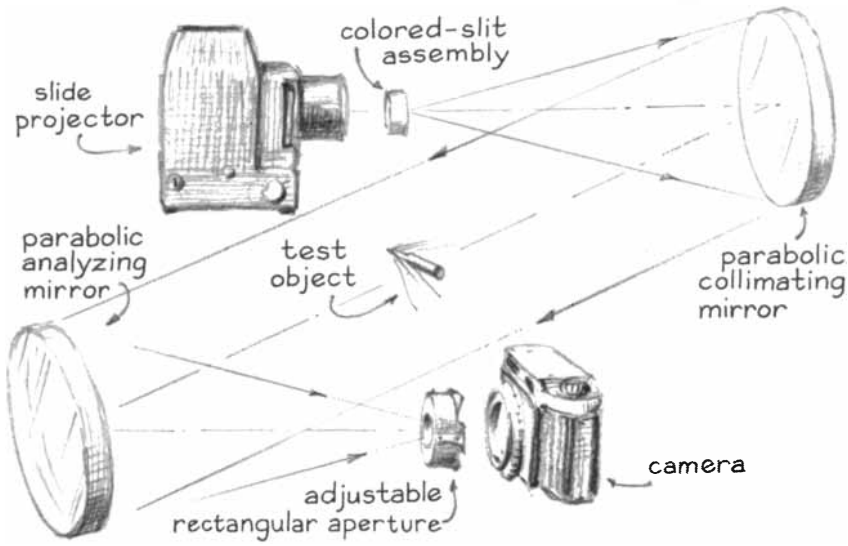
Jet impinging on flat plate



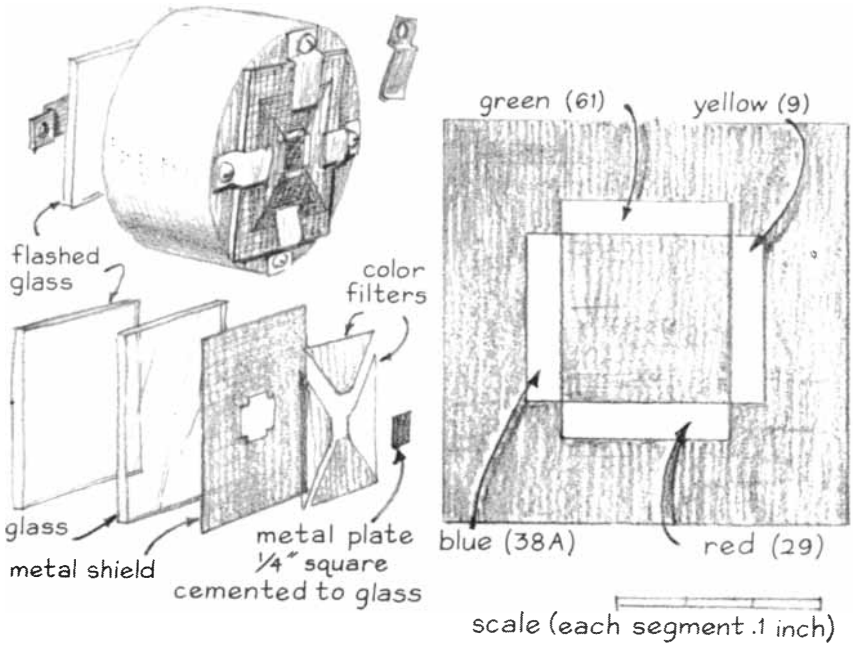
Wedge model in supersonic flow



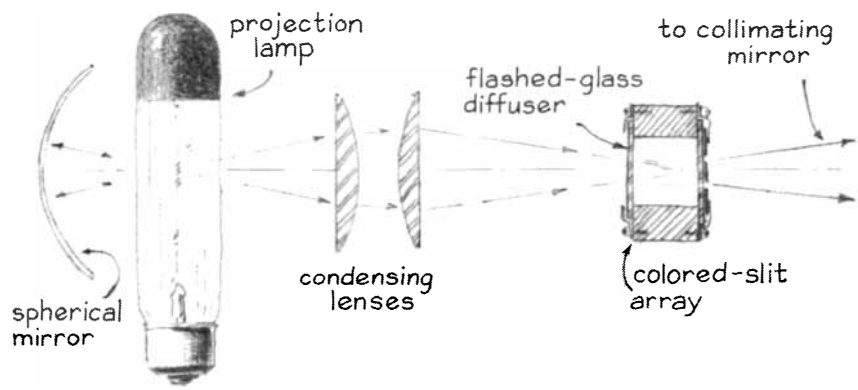
Supersonic airflow over a blunt object



Optical path of Gary S. Settles' schlieren system



Details of the entrance-slit assembly



Arrangement of the light source

to the composite image cannot be distinguished in the black-and-white pattern. Therefore the device shows all density gradients but gives no information about their direction. In practice one black-and-white schlieren photograph is made for each test condition, using a horizontal knife-edge. Additional information is then gathered by repeating the series with the knife-edge fixed in the vertical position.

"A number of schemes have been devised for making schlieren photographs in color. The first of these approaches was described some 30 years ago by Hubert Schardin in Germany. A line source of white light, such as the straight filament of an incandescent lamp, is placed in front of a small achromatic lens. The rays emerge from the lens and pass through a slit to enter a prism that disperses the light into its constituent colors. The dispersed rays are focused onto the first mirror, where they are reflected to focus on an exit slit from which they proceed to the film. The exit slit is adjusted to transmit light of a selected color, for example yellow.

"In still air the film is uniformly illuminated in yellow. Air currents in the test section bend the rays, just as in the black-and-white system, so that some yellow rays are diverted from the second slit and do not reach the screen. These rays are replaced on the screen by rays of another color, yielding a multicolored image. Increasing air densities are depicted by colors near one end of the spectrum and decreasing densities by colors at the opposite end. In effect the system color encodes differences in air density.

"A second method of making schlieren photographs in color was described in 1954 by R. J. North of the National Physical Laboratory in England. In this system the prism is omitted and a set of filters in the form of three strips of gelatin of different colors (such as red, yellow and blue) replaces the second slit. The image of the light source falls on the central strip, which may be yellow. The yellow rays proceed through the system and fall on the film. When air in the test section is undisturbed, the film is uniformly flooded with a background color of yellow. Variations in air density cause rays to fall on the red or blue sections of the filter to form an image in polychrome.

"Recently I developed a schlieren system that appears to be novel in that it displays variations of density in all directions and tags the direction of each variation with a distinctive color. Light

enters the system through four slits in a rectangular array [*see middle illustration on opposite page*]. Each of the slits is covered by a Wratten filter of a particular color. The rays proceed through the conventional mirror system to an adjustable exit aperture also assembled in the form of a square.

"The light from the source is thus dissected into four colored bands: green, yellow, blue and red. (The numeral accompanying each color in the illustration designates the number of an appropriate Kodak Wratten filter.) Other colors can be used, but I have obtained the best results with this combination. The filters could be made photographically. My filter was made by applying colored gelatin strips directly to a glass cover slide and masking the opaque areas with black electrical tape.

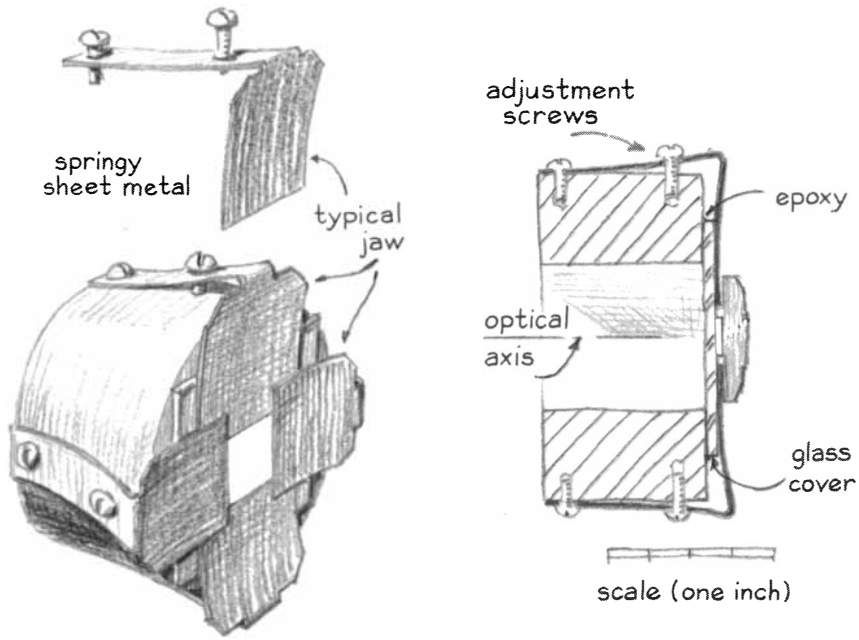
"The light source should be white or nearly so and large enough to flood the slit assembly. The slits should be at least 1/4 inch long and are typically about .01 inch wide. The narrow slit width imparts high sensitivity to the system and the 1/4-inch slit length keeps the exit aperture large enough to avoid undesirable diffraction effects, which spoil the sharpness of the image.

"The light source must be relatively intense to provide adequate illumination for making reasonable exposures. A 750-watt slide-projector lamp with a filament grid about 1/2 inch square serves as an adequate source. A small condensing lens can be placed between the source and the slit assembly to increase the illumination. The source can be further intensified by putting a reflector behind the lamp. If the source does not illuminate the slit assembly uniformly, insert a piece of flashed glass, which is a white, translucent material, between the source and the slit assembly. Ground glass can be used, but it is inefficient compared with white flashed glass, which is readily available from dealers in sheet glass.

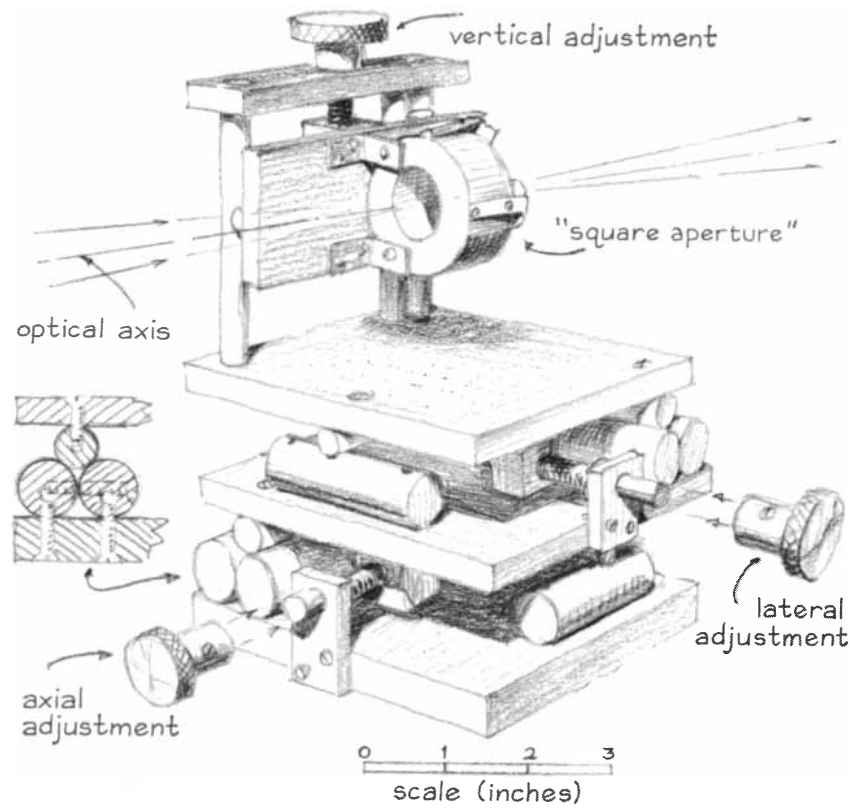
"Light from the colored slits mixes to form a single color in the test section but is refocused into an image of the colored slits at the exit aperture. The exit-aperture assembly consists of four knife-edges cut from springy sheet metal and fastened to a metal collar with adjustment screws [*see top illustration on this page*]. The dimensions of the exit aperture should match those of the companion square at the entrance slit.

"When the instrument is assembled, the entrance slit and exit aperture are placed in the focal planes of the respective parabolic mirrors. The focal length of the mirrors should be at least 11 times their diameter (a focal ratio of $f/11$). Faster focal ratios, such as $f/8$, encourage coma. Slower focal ratios needlessly increase the length of the instrument. Moreover, at $f/11$ the curvature of the mirrors approaches that of a sphere, which is somewhat easier to make than a parabola.

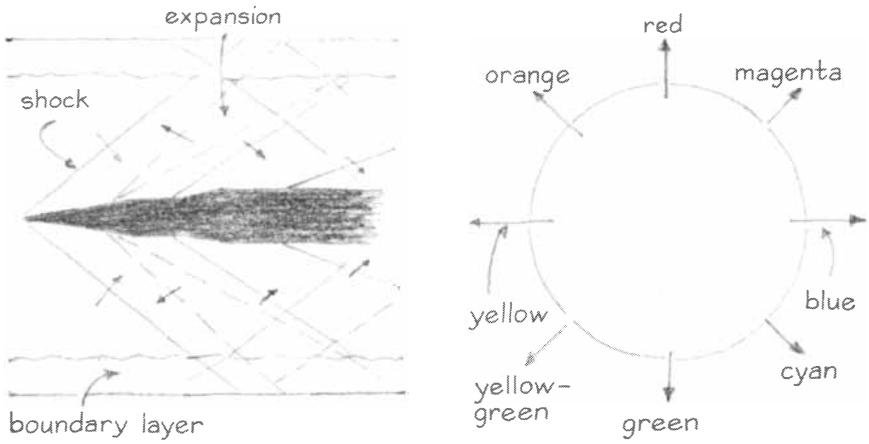
"The light source, entrance-slit assembly and parabolic mirrors should be mounted on a flat, solid base with rigid fixtures. The instrument is sensitive to vibration. The entrance-slit and exit-



Details of the exit-aperture assembly



Adjustment fixture of the exit-aperture assembly



Color code of density gradients

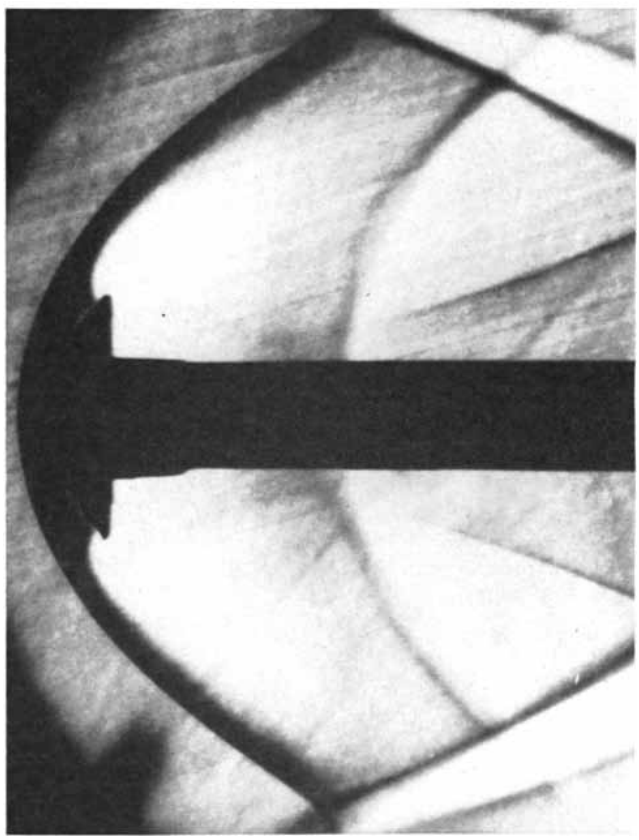
aperture assemblies are located exactly in the focal plane of the mirrors. The position of all four components must be established experimentally as you assemble them.

"The exit-aperture assembly is mounted on a fixture that provides for screw adjustment in three dimensions [*see bottom illustration on preceding page*]. Although this fixture may appear formidable at first glance, it is in fact rather easy to make with ordinary hand tools. The sliding ways consist of drill-rod stock that can be ordered by dealers in hardware. The flat stock can be aluminum plate. The ways and riders can be fastened with epoxy cement instead of screws.

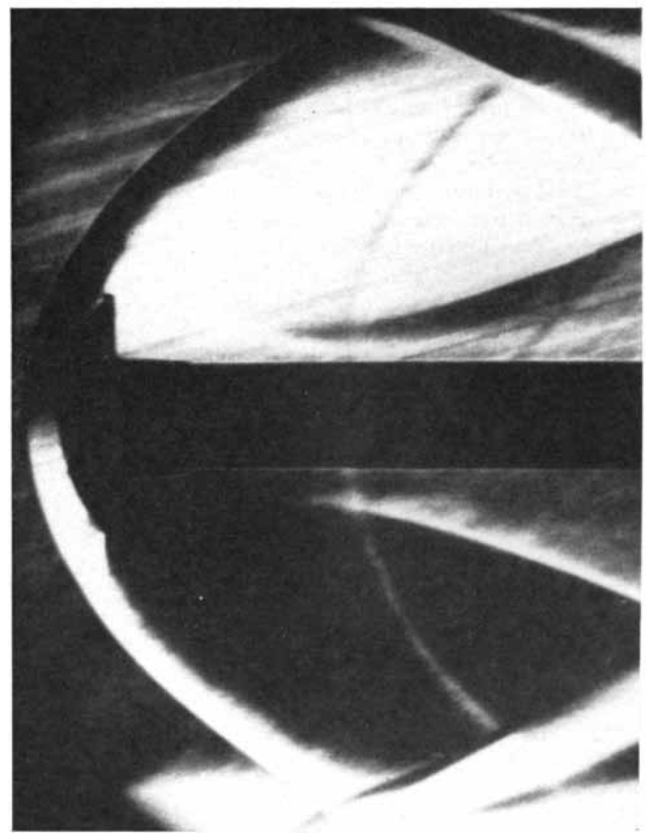
"To align the instrument during assembly first place the source slit at a distance from the first parabolic mirror equal to the focal length of the mirror. Flood the slit assembly with light. The second parabolic mirror can be positioned at an arbitrary distance from the first. Adjust the angle of the first mirror in the vertical and the horizontal plane so that the second mirror is flooded with light.

"At a distance equal to the focal length set up a screen of white cardboard that faces the second mirror. Adjust the second mirror to project an image of the entrance-slit assembly on the screen and move the screen toward or away from the mirror as necessary to create the sharpest image of the entrance slit. Center the adjustment screws of the fixture that supports the exit-aperture assembly, place the fixture in the position occupied by the screen and with the adjustment screws move the exit aperture into exact register with the image. When you have completed these steps, adjust the jaws of the exit aperture to intercept about half of each color band of the entrance-slit image.

"Disturbances that alter the density of air between the mirrors cause weak images of the color bands to shift at the exit aperture. The direction in which they shift determines which colors pass through the aperture to illuminate the schlieren image. The appearance in the image of one of the pure colors, such as red, yellow, blue or green, necessarily corresponds to an entirely horizontal or an entirely vertical deflection of the light

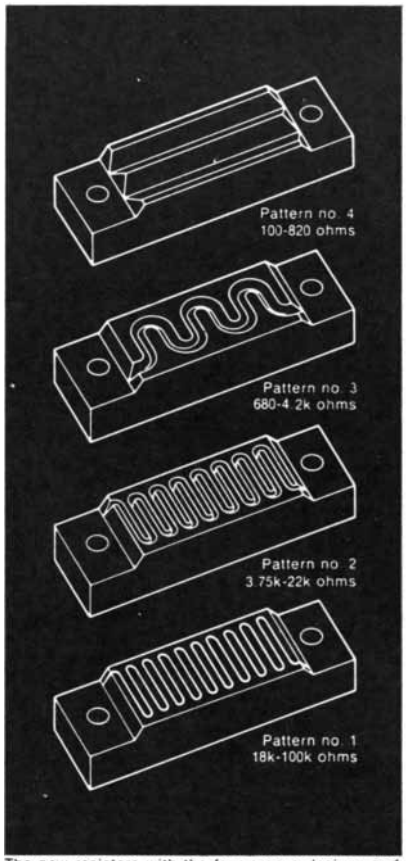


Supersonic flow over vertical knife-edge

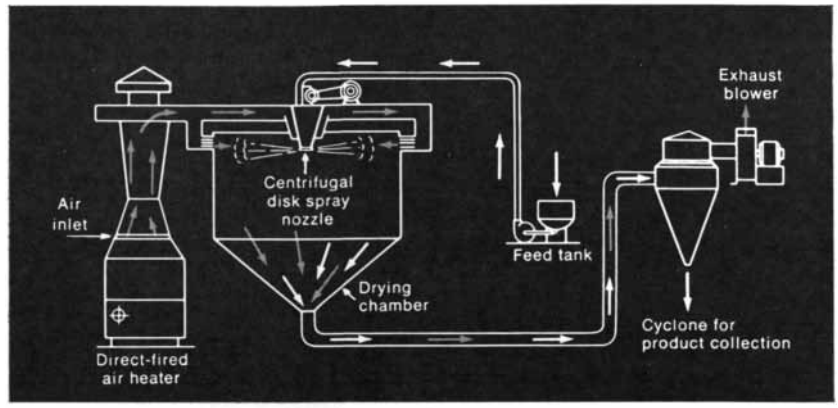


Supersonic flow over horizontal knife-edge

Putting resistance into new grooves.



The new resistors with the four groove designs and the range covered by each.



The spray-drying process that turns the wet ceramic into a fine powder with spherical granules.

Surface of original ceramic (left), and, (right), with finer grade of silica.

Everybody knows the virtues of tantalum for resistors in thin film circuits. Could these virtues be transferred to discrete resistors that would cover a wide range of values, and also be easy and economical to make?

That would involve, essentially, finding a way to deposit a resistor path — i.e., a strip of tantalum — on a ceramic substrate so that its length and width could be closely controlled.

The problem was given to engineers at Western Electric's Winston-Salem plant, and they solved it by designing a small ceramic rectangle which had a V-shaped groove on one surface. Coat that surface with tantalum and then grind it off: tantalum will be left in the groove, giving us our resistor path. Continued grinding keeps narrowing the resistor path. Hook the grinder up to an ohmmeter and it can be made to stop automatically at the desired resistance. With four groove designs we could cover the entire range from 40 to 100,000 ohms.

So far so good. But actually making these little ceramic rectangles with their little grooves presented another problem: what to make them out of. The most promising ceramic had two drawbacks. First, it developed needle-like crystals, giving it the surface you can see on the left of the picture, and tantalum sticks best to smooth, glassy surfaces. Second, the only way anybody had ever made anything out of this ceramic before was by a wet extrusion process. We couldn't extrude these little rectangles because of those wavy grooves.

Our engineers solved the first problem by changing the formulation of the ceramic, and the second by spray-drying it in a blast of hot air. Spraying broke it up into tiny droplets which were formed — by surface tension — into spheres, and that's the way they dried. So now we had a powder made up of spherical granules, which flowed almost like a liquid. That made it easy to get it into individual molds where each resistor substrate, complete with grooves, could be stamped out individually.

Development of even so homely a device as a new resistor is important to us at Western Electric because most of the electronic equipment we make is so complex—and because we make so much of it. Even a slight increase in long-range stability, and fractional reductions in initial cost, result in savings big enough to help the Bell telephone companies keep down the cost of your phone service.

Western Electric

rays, depending on the orientation of the entrance-slit assembly.

"Similarly, deflection in any other radial direction causes two adjacent colors to move into the exit aperture. Part of the schlieren image then appears on the film as a mixture of the two colors. The resulting pattern of color identifies the direction in which light is deflected by corresponding portions of the test region. This effect, together with the knowledge that light is deflected toward regions of higher air density, enables the experimenter to use the instrument as a powerful tool for the analysis of airflow.

"In effect the system displays in one color photograph information that would otherwise require at least two black-and-white schlieren photographs made in sequence. The performance of the instrument is illustrated by three of the accompanying photographs that show density gradients in air flowing over a blunt object at three times the speed of sound. The model in this case is the head of a carriage bolt. One black-and-white photograph [*bottom left on page 122*] was made with the knife-edge in the vertical position. Note the absence of details in the wake of the body. Boundary layers that are actually present on the walls of the wind tunnel and on the model do not appear.

"The second black-and-white photograph [*bottom right on page 122*] was made with the knife-edge placed horizontally. In this photograph the boundary layer and wake region are clearly visible, but the illumination changes sign across the center line of the test section, so that half of the image is white and half is dark. The dark region near the silhouette of the model tends to confuse the shape of the model and to obscure the details of lesser gradients in the region.

"The missing details are apparent in the accompanying color photograph [*bottom right on page 119*] of the same model, which was made under the same conditions. Features of the wake and boundary layer appear simultaneously, as do the shock waves and expansions. The black silhouette of the model appears in sharp contrast to the colored stream of flowing air.

"The instrument can be used for investigating effects other than those that appear in supersonic wind tunnels. For example, one of the accompanying photographs [*top right on page 119*] depicts a jet of acetylene gas impinging on a flat plate. Before striking the plate the vertical jet appears primarily in yellow and blue, indicating increasing density toward the center of the jet. After striking the plate the jet spreads horizontally, changing to red (and green, which is not evident in the photograph) as the density decreases toward the center.

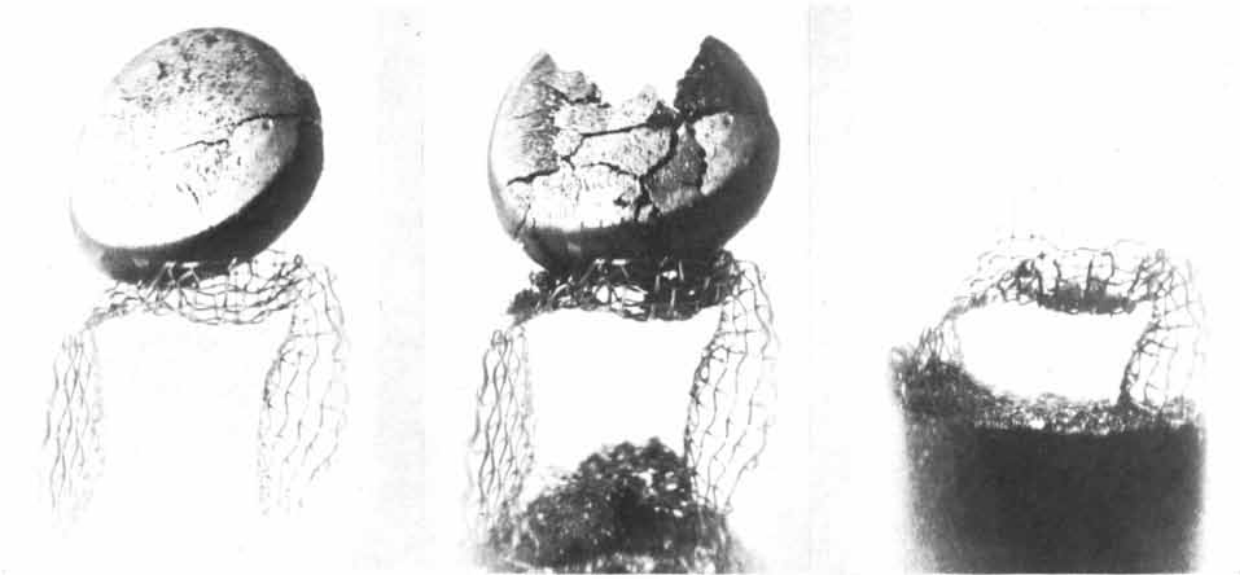
"In its present state of development the system is not useful for measuring quantitatively the density of the medium involved. Such determinations are routinely made with an interferometer. The four-color schlieren system is capable of a quantitative determination of the radial directions of the density gradients in a test object.

"One possible source of error must be considered in applying the four-color schlieren technique, particularly if the color scheme differs from the one that has been described. Assume that the basic colors red, yellow, green and blue are selected for a certain application. The additive mixture of blue and red, blue and green, yellow and red or yellow and green causes no problems, because these combinations yield the expected colors magenta, cyan, orange and yellow-green. If the red and green or yellow and blue should mix, however, an ambiguous result will be observed in the schlieren image because red and green combine to form yellow, and the complementary colors blue and yellow combine to form white.

"The obvious solution is to place red and green filters on opposite sides of the slit assembly and to place the yellow and blue filters similarly in opposition. This arrangement takes advantage of the fact that adjacent colors mix whereas opposing colors can merely replace each other in the schlieren image. When the filters are positioned as suggested, colors in the image can consist only of the four basic hues plus various shades of magenta, cyan, orange and yellow-green, depending on the direction of the refracted light.

"Another possible source of error is the astigmatism that often plagues schlieren systems. It causes the horizontal and vertical bands of the entrance-slit image to come into sharp focus at different points along the optical axis. The solution involves displacing the jaws of the exit aperture correspondingly along the optical axis.

"The concept of a direction-indicating color schlieren system is not new; Hans Wolter of Germany did it with a color-filter exit slit some 20 years ago. It is the idea and the quality of this four-color method that are new. The results of the technique, as shown by the accompanying photographs, are quite an improvement over other color schlieren methods."



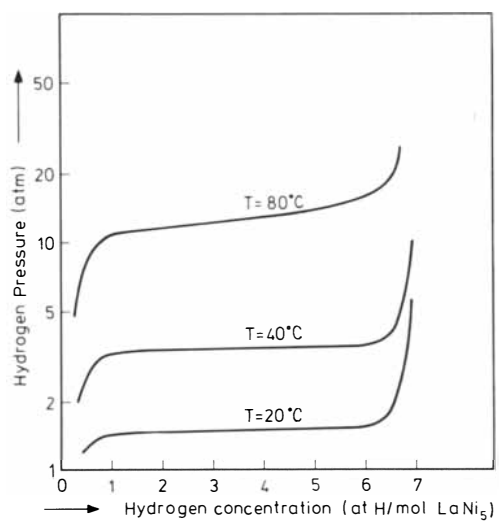
Our magnet attracts hydrogen

This is another example of the way in which relatively straightforward experiments occasionally produce surprising results.

In the research for more powerful permanent magnets, scientists have recently turned to intermetallic compounds like cobalt-rare earth. The properties of this new class of materials are markedly superior to those of conventional permanent magnets. For example, in 1969 Philips developed a samarium-cobalt ($SmCo_5$) magnet with a maximum energy product $(BH)_{max}$ of 20×10^6 gauss-oersteds and a high coercivity (10000 oersted). Etching of $SmCo_5$ powders has a noticeable effect on the coercivity H_c. This led physicists from Philips Research Laboratories, Eindhoven, the Netherlands, to believe that hydrogen had something to do with the H_c. So Dr. H. Zijlstra and Dr. F. Westendorp decided to investigate the coercivity in pressurized hydrogen. A sample of powdered $SmCo_5$ was compressed into a solid cube. This was enclosed in a thin stainless-steel tube. When the sample was subjected to a pressure of 20 atm. at room temperature, the scientists were surprised to find that the change in coercivity was much larger than they had expected; in fact it decreased by a factor of 10. Further experiments showed that large numbers of hydrogen atoms penetrated the lattice structure of the sample, transforming the original hexagonal structure into a hydride of orthorhombic structure, $SmCo_5H_{2\text{-}6}$. When the pressure was reduced, the coercivity regained its initial value and the absorbed hydrogen was released. Pursuing this line of research with structurally related compounds like rare earth-nickel revealed even more exciting results. $LaNi_5$ in particular, a non-magnetic material, easily absorbs more than 6 hydrogen atoms per formula unit. The lattice expansion that goes with it (25% in volume) cracks the compressed pellet (see top picture). The hydrogen gas is as readily released as it is absorbed. A temperature difference of a few degrees or a pressure difference less than one atmosphere spells the difference between nearly saturated absorption and near desorption and it all happens at very practical temperatures and pressures (see bottom figure).

This spongelike property comes in handy for many applications. For example storage of hydrogen, for which the packing densities of H atoms at room temperature can be higher than in liquid H_2, or purification of hydrogen, as no impurities can penetrate the lattice of the material.

So who cares if $LaNi_5$ doesn't attract iron? It certainly attracts hydrogen!



In the Research Laboratories of the Philips group of companies, scientists work together in many fields of science. Among these are: Acoustics, Cryogenics, Information Processing, Mechanics, Nuclear Physics, Perception, Solid State, Telecommunications and Television.

PHILIPS

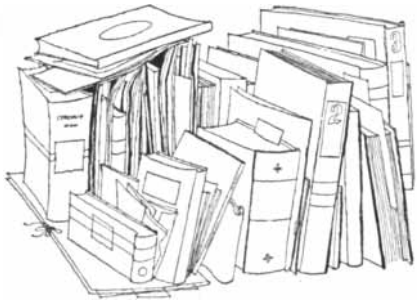
Standard Oil of N.J. terminal facility, Kharg Island, Persian Gulf.

PHOTO: HARRY REDL/BLACK STAR.

SCIENTIFIC AMERICAN

Will devote the entire September 1971 issue to

ENERGY and POWER



BOOKS

Encounters and conversations during the growth of quantum mechanics

by Philip Morrison

PHYSICS AND BEYOND: ENCOUNTERS AND CONVERSATIONS, by Werner Heisenberg. Translated from the German by Arnold J. Pomerans. Harper & Row, Publishers ($7.95). The best-known of those once young men who out of a heap of hints and insights forged quantum mechanics, most powerful and most subtle of all great physical theories, is now 70. In 20 cool, brief chapters he spans a lifetime of "encounters" with friends and ideas, didactically reconstructed out of 50 years of science "rooted in conversations." These fascinating wordy colloquies are not, of course, literally reported. Heisenberg follows the method of Thucydides: "Each orator [is made to] speak as, in my opinion, he would have done in the circumstances." Nor is the book an autobiography, "a collection of memoirs"; the events are all modified and condensed, retaining only "the broader picture" and "the precise atmosphere." Neither is the book easy and flowing; the speeches are not brief, the arguments are tough-minded and each side—whether in nationality, language, science or morals—is given its due. The issues remain before us in unending tensions: positivism v. deep structure, national continuity v. conscience, high ends v. cruel means.

A few of these conversations, as far apart in time and in ambiance as one man's life allows, will sample these sober tales. In 1920 Heisenberg studied with Arnold Sommerfeld at Munich. For two years he lived in two worlds: the flowery alpine footpaths and open, singing youth of the high country, and the taut sophistication of the physics seminars. Wolfgang Pauli, "dark-haired [and] with a somewhat secretive face," a night bird and a frequenter of bar and café, was his friend and fellow student, saturnine critic and foil from the day they met until Pauli died in 1958, still the deep skeptic and prober. "My real scientific career only began," writes Heisenberg, in the afternoon of a summer's day in 1922, on a walk with Niels Bohr over the sunlit Hainberg behind Göttingen. Bohr, then 37, at the peak of his success with the old quantum theory, had been shaken on one point by a criticism made by young Heisenberg, who had worked up the matter (the second-order Stark effect) for a seminar in Munich. That day molded Heisenberg's career: Bohr explained that it was not the form of his planetary model of the atom but the problem of the unique stability of the properties of atoms that had been his starting point. The orbital model was merely a language, "as in poetry," to create images and make connections. This emphasis on the primacy of intention and image over logic in the half-intuitive, contradictory unraveling of the atom was not forgotten; Heisenberg recalled it in 1927, when in Copenhagen he began to recognize the uncertainty relations that fixed—but not too well—the path of an electron in the cloud chamber and that limited an imagined gamma ray microscope.

The last dozen years find Heisenberg a somehow less self-sufficient actor in the role of the old Einstein, once the public mentor and Heisenberg's antagonist in those famous controversies over God's penchant for dice-throwing, which remains the manifesto of quantum mechanics. Heisenberg has now found his own form of a unified field theory—Platonic in connotation, based, to be sure, on quantum fields and not on classical ones—in which he hopes to net the fish of the world. Not many follow him; the younger physicists doubt, and wait for more guidance from detail. He feels, however, that "there will always be young people enough to think about the wider context, if only because they want to be absolutely honest in all things. And that being the case, their number is unimportant."

The moral climax of the work is the terrible and tangled years from 1933 to 1945: the farce and the tragedy of the Third Reich. First is an encounter with a young Brownshirt, listening at lunchtime to Heisenberg practicing the Schumann A Minor on the grand piano of the institute in Leipzig. They part on good terms, although the young man, who sees himself as an impatient idealist anxious to make a new, honest, self-respecting Germany, is disappointed by his physics teacher's old-fashioned morality. If heads are broken and coarse language is used, at least out of the travail change will come, in all vigor and unity. Heisenberg seeks out the old Max Planck. Planck has spoken even to Hitler himself to oppose the destruction of the universities by the ruthless dismissal of the Jews. Hitler "has lost all contact with reality. ... A man like that can only lead Germany to disaster." Heisenberg decides not to leave Germany but to remain there, surviving through compromise until the "time after the catastrophe," when one could help young people to build a new and better world.

But Hitler's cause is very bad, and the British and the Americans will persist to the bitter end in their "horror at the crimes of the National Socialist system, particularly in racial matters." We never see the holocaust more explicitly than that. Indeed, the flames of war are visible in the book only when the Allied bombers come to burn Berlin, to kindle the house next door, to engender among the flames a meeting with the new neighbor, a "white-haired old gentleman," Herr von Enslin, who had the "characteristic Prussian attitude I had always admired: simplicity, discipline and few words."

The Americans built and used the bomb, that bomb which Heisenberg had in 1941 tried to hint to Bohr the Germans could never build. Bohr was so horrified that he failed to take the hint, and "perhaps he was also too filled with justifiable bitterness." In their first postwar meeting the two old friends could not agree on what had passed between them then, and "both came to feel that it would be better to stop disturbing the spirits of the past."

In 1956 and 1957 Heisenberg joined in political statements against German possession of atomic weapons, but he comes to hold that such acts are of little value when they are general, without

binding force, so that governments can merely include them in their calculations. (American readers, whose president seems determined to wind down our war by mounting the largest sustained aerial bombardment of all time and by supporting new incursions into two countries, will take his point easily.) "You cannot be a good politician and a good scientist at the same time. Nor could it be otherwise. What matters in both is wholeheartedness."

The 20th century is saturated with ironies. Heisenberg's candid and yet somehow incomplete volume fits it extremely well. American physicists certainly have no right to inveigh against a slightly weary nationalism and an honestly blinkered view. One needs to remind oneself that Heisenberg has undertaken to write these lines, both those he believes and those he doubts. No reader can fail to acknowledge a debt of gratitude for this evocative essay in memory, philosophical argument and moral stance.

There is one story that deserves repetition. While Bohr was summering in a cottage in the woods at Tisvilde, his neighbor, who was not a superstitious man, had a horseshoe put up over his door. They asked him: "Do you honestly believe [it] will bring you luck?" "Of course not," the man answered, "but they say it helps even if you don't believe in it."

ORIGIN OF EUKARYOTIC CELLS, by Lynn Margulis. Yale University Press ($15). "Everything has a history," writes Professor G. E. Hutchinson in his foreword to this attractive, enthusiastic and learned volume. More particularly, living organisms have a history; that history, played out on a stage of free energy flow by the statistically reproducing actors of natural selection, is the only general biological history, namely evolution. For 50 years after Darwin biologists cultivated their phylogenetic trees. These were subjective, wishful and barely testable, everything that today's sharp, reproducible and tightly argued molecular biology is not. Trees are out of fashion. But who can tell us how point mutations and sundry tape doublings, crossings and writhings made the oak and the squirrel, the gull and the gall by summing up the changes in many a piece of enzyme? We need a wider view, even if it is not at all in such crisp focus.

Mrs. Margulis, a young Boston University biologist, has taken up the challenge. Her thesis is plain: the great gap between the cells with true nuclei (*eu*plus *karyon*), which make up every living form from the paramecium to the whale, and the more primitive prokaryotes was never closed by a single strange intermediate cell. Such a cell would have to be a missing link more hybrid than any mermaid. "Every free-living organism can be unambiguously classified either as prokaryotic [that is, small, without nuclear membrane, dividing without complex mitotic apparatus] or eukaryotic [large, membrane-bound nucleus, classical mitotic spindle for orderly division]. No single organism ever filled that great evolutionary gap. The time has come... to explore the consequences of the concept that all animal cells had three, and all plant cells four, independent prokaryotic ancestors."

Each cell of almost every higher form contains several classes of vital organelles. First comes the membraned nucleus itself. Next are the tens or hundreds of mitochondria, the enclosures where the complicated biochemical machinery of the Krebs cycle is mounted, producing most of the cell's ATP fuel by the oxidation of small organic molecules. Third is the moving fibrous structure that manages the rigging of the mitotic machinery, causes protoplasmic drift and in closely related form is the ciliar apparatus that propels certain cells. An optional organelle is the intricate chloroplast, where in all green plant cells the competence for photosynthesis resides. Only the prokaryotic blue-green algae can employ chlorophyll that is not packaged into the layered plastids of the green leaf; some bacteria, also prokaryotes, photosynthesize even without the green stuff.

The argument of the book is now plain: the higher cells represent a symbiosis. A mutually beneficial act of association has grown into a necessity, joining forever the organelles, once tiny free-living cells, and their larger host cell that once lacked the special expertise conferred by the organelles. The concept is not new; it was the view of the cytologists of yesteryear, such as E. B. Wilson, who examined and codified the visible life stories of many kinds of cell long before a deeper molecular analysis became possible. But our new understanding gives this picture far greater force today. Here are the electron micrographs of the symbiotic inclusions in many an unusual protozoon, demonstrably giving the assemblage novel biochemical powers. Nowadays we can separate a lichen into an alga and a fungus, or a paramecium into the host and kappa particles. The nucleic acid content of many of the extranuclear organelles makes sense on this theory, as do many special mechanisms for the transmission of organelle instructions that are not recorded in the central nuclear data bank. The genetic code of the symbiont is typically inherited by way of the female line, in the cytoplasm-rich egg, and not by way of the cytoplasm-poor sperm. The alga *Euglena* can easily lose its green under a variety of dysgenic treatments. But no *Euglena* has ever regained its chloroplasts by a back mutation; that would be "equivalent to the probability of the spontaneous generation of blue-green algae."

Experimental predictions are not lacking, and a few results are already in hand. Drugs that inhibit the operation of the mitotic spindle, such as colchicine, seem equally to prevent the growth of the fringe of cilia on *Stentor*. The very letter frequencies of the DNA code—the crude representation of the proportions of different bases that is our present best cryptanalysis of most DNA messages—display a greater variation among the prokaryotes, all of them tiny single cells, than over the entire range of the higher animals or of the higher plants. The ribosomal RNA of, say, a toad cell comes from a font of molecular type whose letter frequencies are closer to those of the nuclear DNA of a cow or of a spinach plant than they are to the mitochondrial DNA in the very same cells of the same toad species. Those organelles retain the foreign code they brought the day they joined the firm.

The most fascinating implications are for the origins of life, which Mrs. Margulis discusses at length. The enduring aeons of Precambrian time evolved those complex, distinct prokaryons. The relatively short period since then shows what cells can do corporately. Our natural-history museums are thus displays of the power of microsymbiosis. In a more general sense this viewpoint gives strength to the entire evolutionary picture, from the time before there was any life up to today. In all sequential random processes an enormous premium awaits any means of avoiding the necessity of accumulating independent rare events. Life can never start atom by atom. Life demands molecular arrays. It now seems clear that the eukaryotes, and that chain of showy organisms of which we are one late link, could never have arisen gene by gene. Sex too is mainly another mechanism for beating the dealer by keeping winning cards together.

This is an original book, the best kind of contemporary natural history. The

photographs are excellent and the tables and drawings helpful. It is not easy reading, both because of the multilinear nature of its arguments and because of that compact Hellenate jargon dear to biologists. (One admits that the author must deal with a most unfamiliar bestiary, one that surely would have daunted Noah.) Two back-to-back pages of photographs (supplied by the paleontologist Paul F. Hoffman) are memorable: on one side you see stromatolites, limy heads made by reef-forming algae, looking no different whether they are in the two-billion-year-old rock of the "east arm of the Great Slave Lake" or in the present-day tidal flats of Shark Bay in Australia. On the other side the same Canadian rocks reveal in quite similar formations, probably the fringe of an old marine delta, a number of small vertical tubes resembling the burrows of marine worms. Were these tubes some inorganic bubble or the first many-celled organisms, tentatively evolved and bankrupted a billion years before the first symbiotic successes whose legacy we share?

THE MIND OF MAN, by Nigel Calder. British Broadcasting Corporation (2.25 pounds). Ramanand, a calm and large-framed man who for 30 years had been an adept of the practice of yoga, lay in a carefully sealed metal box, visible through a glass port. Over him watched B. K. Anand and G. S. Chhina of the All-India Institute of Medical Sciences, whose recorders followed the vital signs of their electrode-fitted subject as he passed into trance. For hours he lay there, and as meditation deepened his brain waves slowed, his heart and breathing calmed (although he remained feverish) until during the sixth and seventh half-hours carefully withdrawn oxygen samples confirmed his inner state: his oxygen consumption had dropped by a factor of four below the basal metabolic rate. By willing it he had reduced the glow of life to a mere 25 watts of power. As the carbon dioxide content of that trapped air rose, overridden internal interlocks asserted themselves. Ramanand began to use more oxygen, signs of disturbances appeared in the traces and after six hours he pressed the alarm buzzer to seek release. None the worse for the experience, he complained loudest that his ear hurt from a detector affixed to it.

The experiment was public too; it was caught on film by a BBC camera crew, for whom the test, first done a decade ago, was run again. Last October television viewers in Britain, Sweden and the U.S. saw this remarkable demonstration of just how docile the autonomic nervous system can become.

This confident, intelligent and swift-moving book, given more immediacy by many photographs of brain experimenters and their experiments in laboratories from New Delhi to Moscow and Los Angeles, is a remarkably lively piece of science journalism. Its author is the scriptwriter for that television special, who with his producer and camera teams visited eight countries in 1970 to create the show and the book. Calder is a quick study, an outspoken critic, a man impatient of jargon and pretense and an admirer of clarity. His book, like its title, is wide in scope, but it is never pretentious or empty. The grand sweep of the title is deliberate. The single result exemplified by the yogi (also demonstrated with metaphysically more naïve subjects in New York who have been taught by simple tone signals to reduce blood pressure and retard a racing heart) is in a way the motif of the book. The variety and range of the experimental evidence convinced Calder that the mind and the brain are "inseparable." This does not so much degrade mind to matter, he argues, as upgrade matter to account for mind. The simplicities of stimulus-response theory, like the mysticism of the past, are inadequate at a time when "palpable mechanisms" of unprecedented subtlety are being found and grasped. We are, Calder thinks, in the Copernican era of brain research; it is a time for energy and hope.

The book is clearly episodic, although it is by no means without careful structure. It is a survey, an understanding one in the highest sense of that term, rather like a dozen lucid articles on quite different levels of work. Some of the genuine excitement can be gained by a sampling of the topics.

At Cal Tech, Roger Sperry experiments with a young housewife (shown here casually cycling down the road) who has had the direct connections between her cerebral hemispheres cut surgically as a treatment for severe epilepsy. She has "two independent minds" in one skull. "Dexter and Lefty [are] as unlike as Jacob and Esau. Dexter ... is the smart one who does all the talking.... Lefty stands by quietly ... but he is far from stupid ... has the keener sense of shape, form and texture. He can, for example, copy a geometrical picture much more accurately than Dexter can.... Perhaps Lefty's education has been grievously neglected.... We should be paying much more attention than we do to the cultivation of nonverbal skills at school."

At the University of Wisconsin, Harry and Margaret Harlow continue to interfere with the childhood of their experimental monkeys. Who does not know of the terry-cloth "mothers" who inertly grant monkey infants security from the toy robot? Nowadays it is plain that some soft mothering contact is indispensable, but so is play with peers. Six months' isolation in infancy is ruinous; such a deprived monkey mother will reject her own baby. A younger monkey, however, can serve as a "therapist." Even newer are experiments with "suburban life," imposing on the rhesus monkeys a father-mother-infant home. This is quite unnatural for the rhesus father, who normally has little attachment to family. The confined fathers played it rough with the young ones, particularly the males, but those little monkeys became "the most self-confident, self-sufficient and courageous young monkeys we've ever seen."

Then there are the chimpanzees Washoe and Sarah. Washoe has been living with Allen and Beatrice Gardner at the University of Nevada since she was a year old; now she has learned very well the standard gesture language they have taught her. She strings signs for herself into meaningful combinations, such as "open food drink" for refrigerator.

Sarah, who works with plastic shapes arrayed on a board, is older. She has been studying such written language for two years at the University of California at Santa Barbara, and under a more severe and formal discipline engages—maybe—in logical discourse about her symbols and what they mean. She even takes true-and-false tests, like most other students of psychologists. The question of whether or not these animals are merely cleverer than Hans the horse is still wide open.

Then there is Z: Red Army officer Lev Zassetsky. He lost a left rear brain segment to a gunshot in 1943. He found his way to A. R. Luria of the University of Moscow, who recognized that his courage and personality were unimpaired and staunch. Over 25 years Z has written an eloquent 3,000-page autobiography, although when he first appeared as a patient, he had lost the ability to read or write except for being able to sign his name. He has created for himself, says Luria, "an artificial mind," using mechanisms quite different from those involved in normal writing. Z is unable to distinguish spatial relationships: he cannot tell left from right, above from be-

low or whether or not his brother's father and father's brother are the same person. Grammar, calculation and recognition of geometric forms are gone, but Z has begun to contrive new ways of reasoning out the answers.

Not everything new is true. The transfer of learning by RNA remains unverified, and Calder guesses that its supporters are wrong; "otherwise the shape and content of this book might have to be very different."

There is nowhere else to go for so up-to-date, wide-ranging and specific an overview of this remarkable field. That the detail is not deep, and that it is not made easy for a reader to move beyond what is here into more technical material, should be no surprise. This is a new style of introduction to a science, and it is hugely successful in its own terms. It reads even better (if it is not quite as timely or as handsome visually) than the somewhat more cautious effort made by the same team two years ago: a tour of modern astronomy published under the title *The Violent Universe.*

THE GROWTH OF SINGLE CRYSTALS, by R. A. Laudise. Prentice-Hall, Inc. ($14.50). The world tends toward order, not disorder, whenever free energy can be made available by the change from the latter to the former. Every snowflake bears witness to the fact. The cultivation of order in crystalline matter, as in all the rest of nature, is nonetheless a challenge, a kind of molecular gardening. Noise is always present, and seed crystals are small. This expert book is a textbook and "a professional crystal grower's *vade mecum.*" In it the author, who was for a decade the head of the crystal chemistry research department at the Bell Telephone Laboratories, presents the theory and practice of crystal growing, chiefly for solid-state research and development in domains extending from tunable filters to bearings and cutting edges.

The work begins with theory: a brief account of crystallinity, with a mere touch of crystallography and a clear account of imperfections of all kinds; this is characteristically followed by a table of etchants suited to reveal the presence of imperfections in a dozen important substances by careful study of etch pits with the light microscope. The succeeding chapters take up the quasi-equilibrium thermodynamics of crystal growth and the more complicated issues of growth kinetics. Nothing is at any very difficult mathematical level, but the arguments reach a high degree of sophistication. Then there are one longish chapter each on the types of artificial crystal growth: (1) in the solid state, by the slow annealing of strain that forces the recrystallization, with summary how-to-do-it tables for many metals; (2) growth by carefully controlled freezing, with the crystal pulled from the melt to avoid the use of crucibles; (3) growth from vapor, and (4) growth from solution.

This subject is almost universally fascinating in its diversity from the ancient history of gems to ice-nine, Kurt Vonnegut's imagined room-temperature stable polymorph of ice that infects and freezes the oceans! It is of course true that crystal seeding—helping that free energy to fall by providing a small template—is one way of making a start. When Bell Laboratories engineers began to grow piezoelectric crystals of ethylene diamine tartrate from water solution on a production scale, they found strange "barnacles" of foreign material forming on the growing crystals. Not long afterward the same barnacles began to show up in a laboratory miles away. The stuff was infectious; people traveling from plant to laboratory carried its micronuclei. The infecting species turned out to be the same compound incorporating one molecule of water of crystallization per molecule of ethylene diamine tartrate. The cure was a higher temperature and a strict quarantine for keeping grown crystals away from any moisture. There is a good account of the curious instability called constitutional supercooling, the cause of most unintended dendritic growth, where peaks in an interface grow more rapidly than valleys. Diamonds are best grown from a solution of carbon in a molten metal such as nickel or palladium; graphite is the usual source of carbon but other sources, including peanut butter, have been used. A year ago gem-quality diamonds of a size up to several carats were first grown by man.

There are some excellent photographs: a slab of aluminum six inches wide made by strain annealing, its dozen big etched grains forming a strong example of abstract expressionism (New York school, a little dated), and an ice cube showing off its grains by polarized light. Amateurs will profit by looking through this book, but Dr. Laudise quite rightly observes that solution growth, perhaps the most accessible of home techniques, has been most recently and usefully discussed in the books of A. N. Holden and his co-authors. These books, which are intended for secondary school students, detail not only the mason-jar method but also the method of the rotary crystallizer, which can be bought in kit form.

MEGISTOS: A WORLD INCOME AND TRADE MODEL FOR 1975, edited by C. Duprez and E. S. Kirschen. North-Holland Publishing Company and American Elsevier Publishing Company ($35). Claudius Ptolemy's astronomical handbook had the same title as this book. The word is "the superlative of the Greek word for *large,*" and here it connotes the largest possible macroeconomic set of variables: those that refer to the economy of the entire world. The authors are 15 economists of Brussels, who developed their model out of a report one of them had prepared earlier for the United Nations. The work was completed at the end of 1968 on the basis of statistics then available. It is a cool, rather dry, realistic projection of the effects of the flow of commodities and investment throughout the world. The approximations are explicit: the world is represented by 12 zones (including the developed capitalist, the communist and the underdeveloped countries); the trade flow, by 48 commodities (from "clothes not fur" to "oil and oil products"), and a number of fiscal services. The base-line data extend from about 1950 to about 1964. On such a framework the authors first forecast the material product of the developed areas; from this they infer their imports and their aid to the underdeveloped countries and thus predict what foreign exchange is available. From that and from an estimate of the effect of policy decisions within the underdeveloped countries, the "likely growth of gross national product in underdeveloped countries" can be inferred. The approach is not based on plans or other normative proposals but on what the authors, combining mathematics, sociology, politics and common sense, see as facts and trends. It emphasizes foreign exchange, admittedly in part because economists are "lured by the availability of statistical data." The procedure is basically a consistent, interlocked extrapolation of trends, maximizing various growth rates by means of linear programs.

What is most striking to an American reader is the catholicity of the work. The People's Republic of China gets a full chapter. The model used, devised in 1965, is credited to a Japanese economist. The model-builders are definitely committed to the inclusion of judgments about noneconomic factors, from the thought of Mao Tse-tung to the assump-

tion that "North Vietnam will be at peace by [1975]."

The volume presents much useful data auxiliary to the analysis: populations and densities; the full income and trade picture for 1960; Simon Kuznets' well-known gross national product per head for France, the U.S. and Japan retrospectively over a century or more; current commodity flows; oil industry capital and exploration expenses, and Cuban sugar crops. The book of course never comes very close to the wellhead or the cane cutter; it is a collection of dollar figures, head counts and coefficients relating capital investment to output. The authors fit curves to many complex events. For example, there is a way to test for a Central American "common market effect" by looking for deviations from a smooth, fitted exponential before and after the date of an agreement. None showed up reliably.

The conclusions are not surprises. The annual gross domestic product per head in real exchange rates, expressed in 1960 dollars, will in 1975 amount to about $2,900 in capitalist developed countries, $1,500 in communist Europe, $510 in South America and $280 in communist Asia. (Africa and noncommunist Asia set such heavy problems of exchange estimates that the authors confined themselves to growth-rate estimates. One gets $100 to $120 for those two regions in 1975, using official exchange rates.) This factor of an order of magnitude between the developed world and the underdeveloped world is one driving parameter for the history of our epoch.

Growth rates do not give quite so unequal an accounting. Per capita the Red Asians will grow wealthier at the rate of 2.7 percent per year and Asians of other political hues at 2.2 percent. Latin America will gain at 1.9 percent per year, Africa at 1.5 percent. Overall the underdeveloped countries will gain at 2.4 percent, the capitalist countries at 3.1 and the developed communist countries at a lively 5.2 percent, for a world rate of 2.7 percent. The U.S. had a growth rate of 1.5 or 1.6 percent over the entire period from 1850 to 1960, and the book predicts one of about 2.4 percent in 1975. The highest long-range growth rate is Japan's, averaging about 2.5 percent since 1850 and forecast for some 6.5 percent in 1975.

No reference is made to any steady rise in the cost of resources or of their maintenance. Yet no exponential can continue forever. World G.N.P. has its clear limits, but they lie further off than 1975, somewhere this side of 2100.

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