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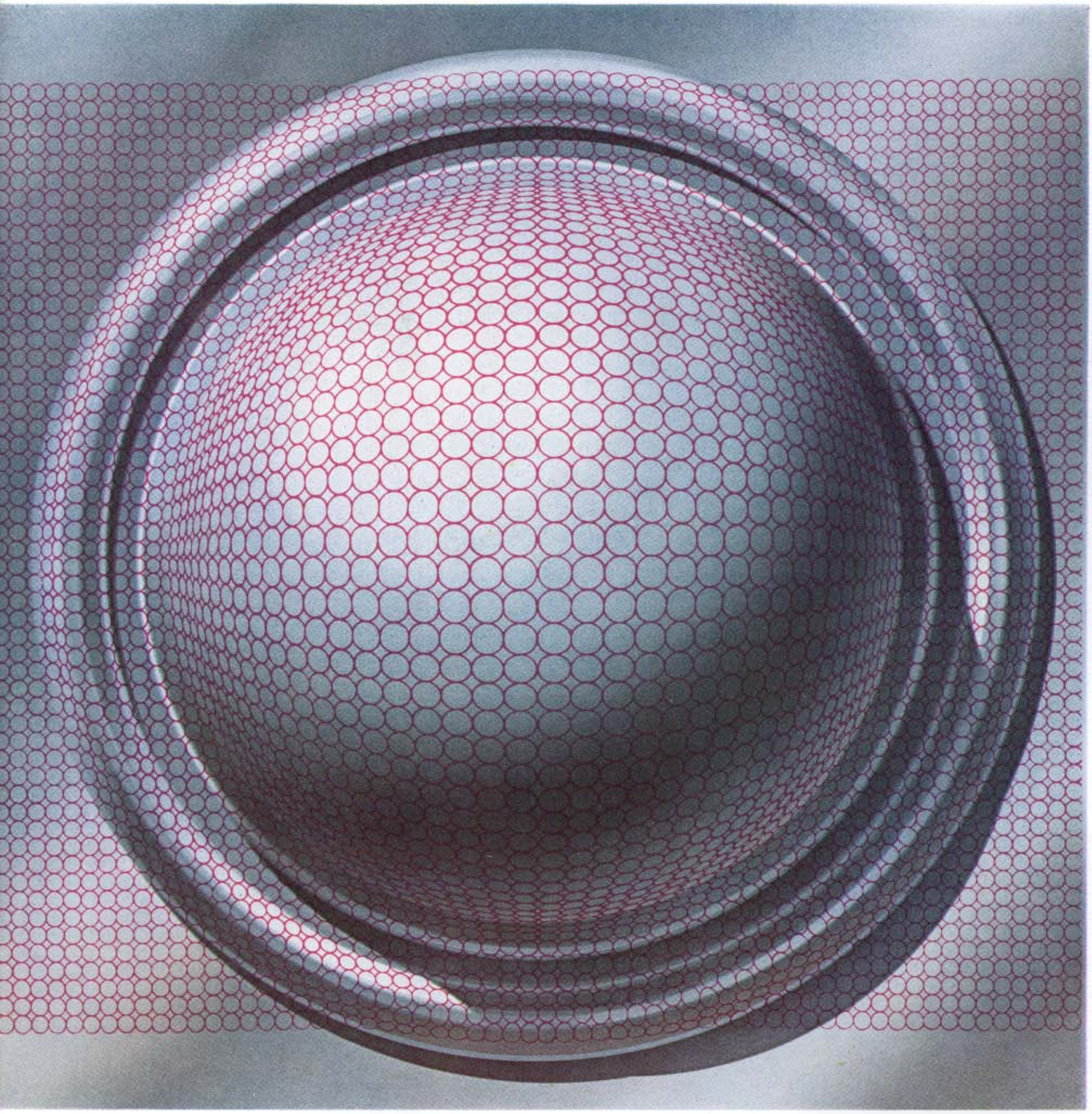

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November 1976

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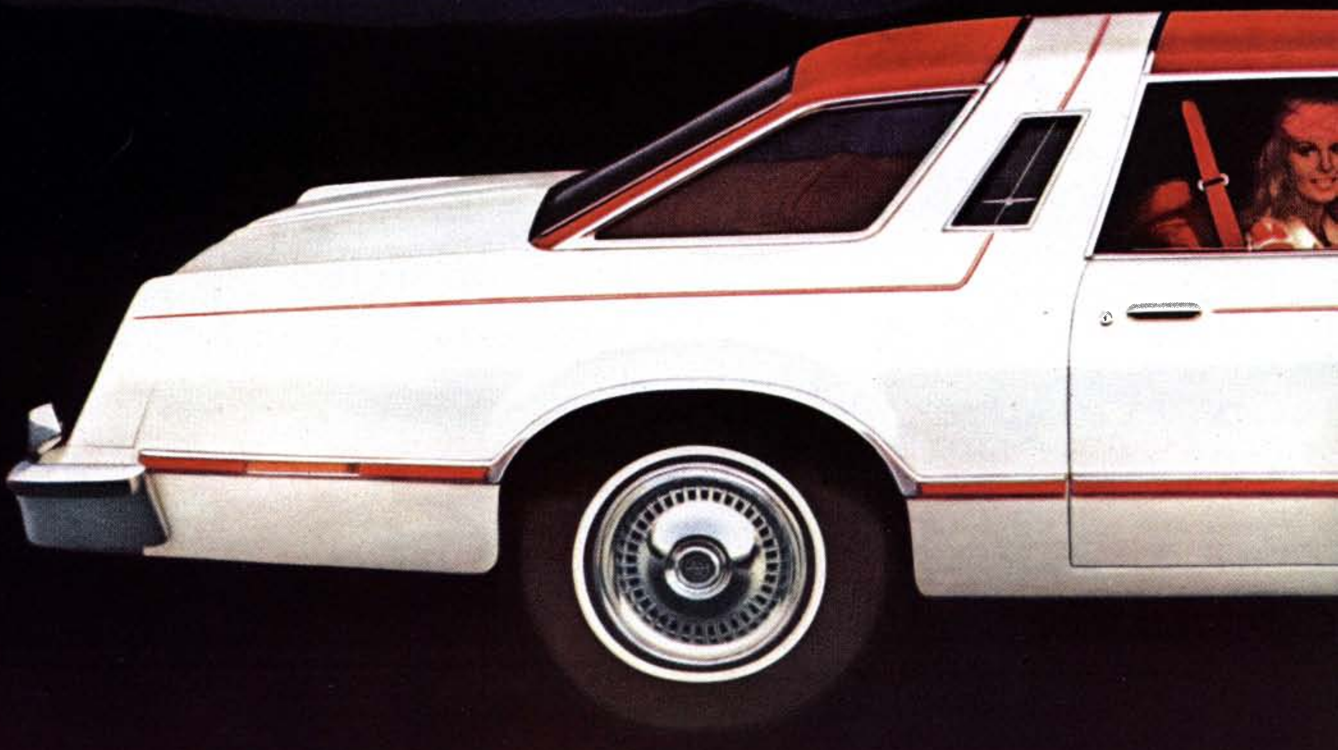


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Letters of recommendation from France.

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Established 1845 **SCIENTIFIC AMERICAN** November 1976 Volume 235 Number 5

ARTICLES

DEPARTMENTS

THE COVER

The painting on the cover shows a piece of sheet metal that has been marked with a grid of circles and then formed into a domed shape by stamping in a press (see "The Forming of Sheet Metal," page 100). The metal is low-carbon steel of the type used for making automobile parts; before stamping it was a flat piece about six inches square. At that time the circles were each 2.5 millimeters (.1 inch) in diameter. After stamping the change in the size of the circles that were affected by the stamping provides a measure of the amount of deformation that occurred in each section of the sheet. The circle-grid method is therefore useful in testing metal for its ability to take the forces of forming and in monitoring stampings made on the production line. The domed shape was made in a laboratory process called a punch-stretch test, in which metal is deformed by a hemispherical punch to test its capacity to stretch during stamping.

THE ILLUSTRATIONS

Cover painting by Ted Lodigensky

Page	Source
28	U.S. Air Force
29–37	Total Communications Industries, Ltd.
39–40	T. G. R. Bower
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45	Alan D. Iselin
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49–60	Andrew Christie
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81	Frank Richter
82–89	George V. Kelvin
90	Carol Donner
91	Alan R. Gibson
92	Carol Donner
93	Andrew Christie
94	Alan R. Gibson (*top left and bottom*), Carol Donner (*top right*)
95	Carol Donner (*top*), Andrew Christie (*bottom*)
96	Andrew Christie (*top*), Carol Donner (*bottom*)
101–102	General Motors Corporation
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108	Ralph Morse
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116–117	Tom Prentiss
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123–125	Adolph E. Brotman
127	James A. Tuck
129	Adolph E. Brotman
133	Harry Turner
134	The Metropolitan Museum of Art
136	Andrew Christie
141	*A Treatise on Limnology.* © 1967, John Wiley & Sons, Inc.
144	Courtesy of the Director of the Victoria and Albert Museum
148	*Herbal.* © 1965, David R. Godine

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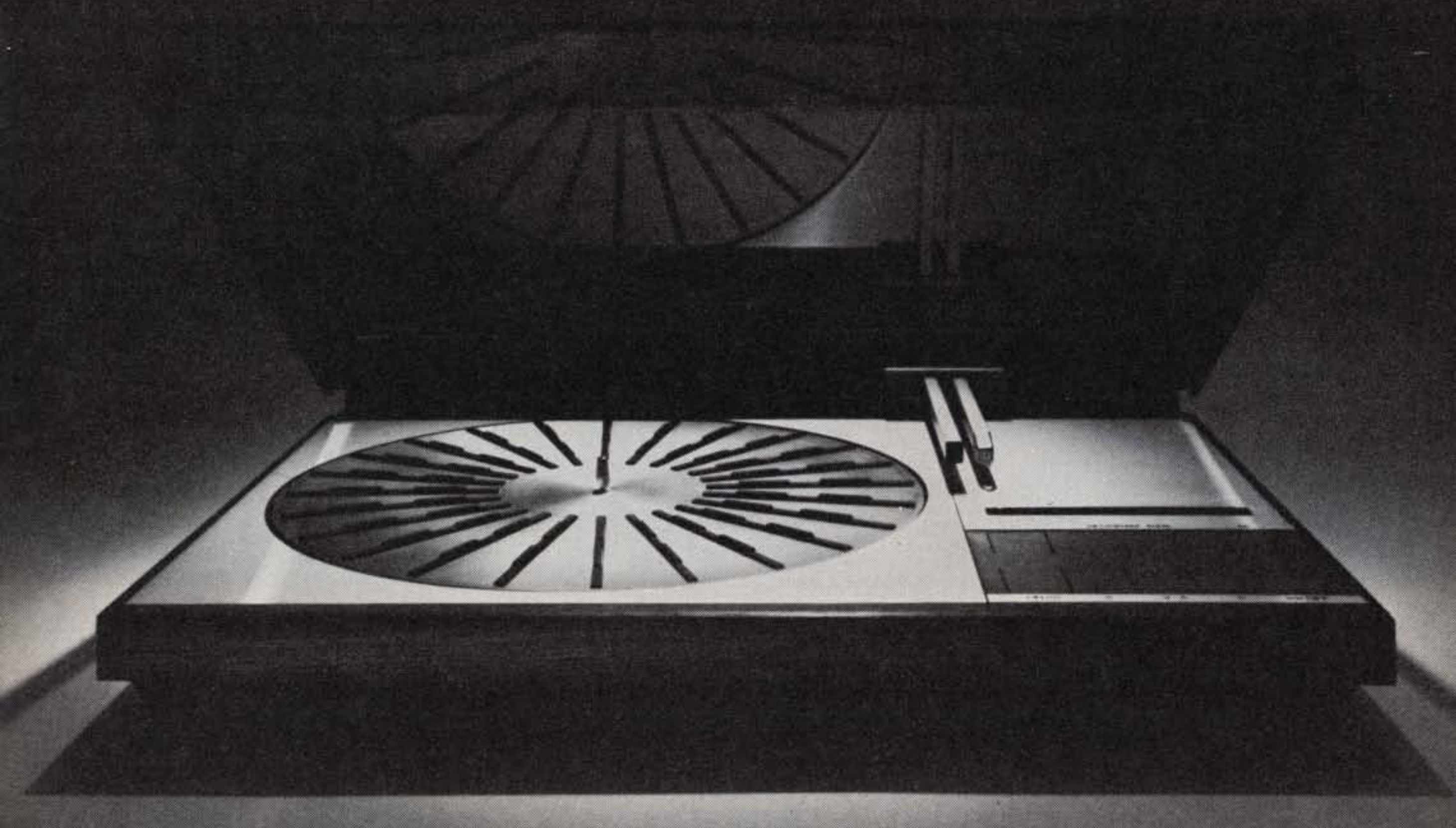

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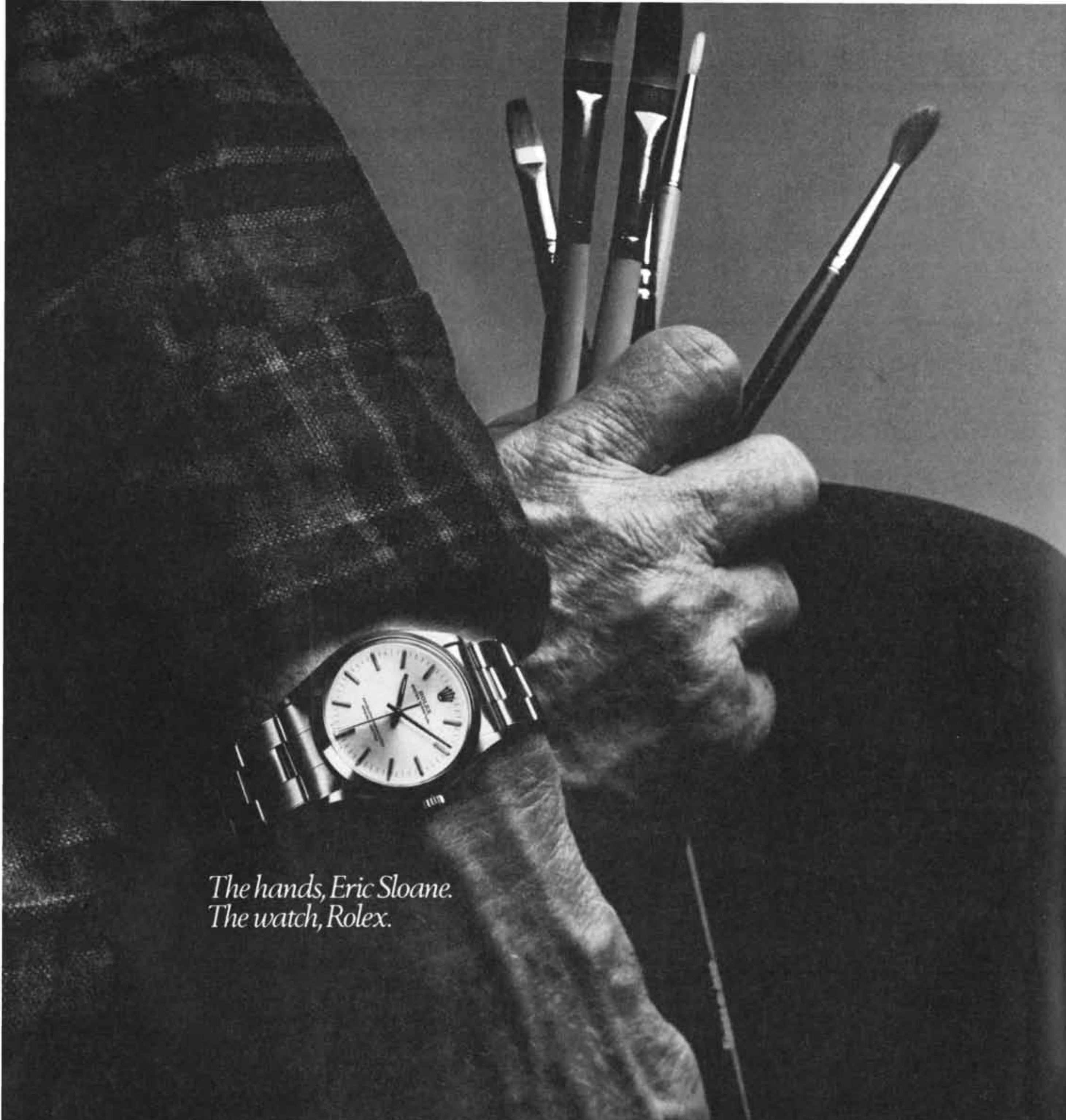
The hands, Eric Sloane.
The watch, Rolex.

LETTERS

Sirs:

I have read with much interest Rüdiger Wehner's "Polarized-Light Navigation by Insects" [SCIENTIFIC AMERICAN, July]. I should like to bring to his attention a point he may have overlooked. Professor Wehner states in the first sentence of his article: "The eyes of insects are sensitive to a natural phenomenon that man is blind to: the polarized light of the daytime sky." Actually the human eye is capable of responding to the polarization properties of light in the phenomenon known as Haidinger's brushes.

When one looks at a source of polarized light, one can observe faint yellow and blue brushlike patterns that are related to the direction of polarization. A simple way of observing Haidinger's brushes is to look at a bright cloud through a sheet of Polaroid; as one rotates the sheet the yellow and blue patterns appear and rotate with it. Haidinger's brushes can also be observed, with some practice, with the unaided eye: one looks at the blue sky and sees the faint yellow and blue brushes, with the yellow brush generally pointing toward the sun. The contrast of the patterns is low, and it takes some time to recognize them. The phenomenon is also subject to visual fatigue, so that one cannot observe it too long in any one session....

BERNARD M. JAFFE

Professor of Physics
Adelphi University
Garden City, N.Y.

Sirs:

Professor Jaffe is quite right in observing that some people are capable of perceiving a rather faint pattern that is caused by polarized light and is known as Haidinger's brushes: a small yellow and blue Maltese cross that appears in the center of the visual field. The yellow brushes are darker than the surround and are perpendicularly oriented to the direction of polarization.

This phenomenon, however, is so close to the borderline of perception that none of the undergraduate students I have asked about it in courses had ever seen it. Even after the phenomenon had been described to them in detail most of them had difficulty observing it with the unaided eye in natural skylight. Even Wilhelm von Haidinger, who first described "these flying phantoms of yellowish color" in 1844, could not observe the phenomenon without specially cut mineral crystals. Although Haidinger's brushes are of no functional significance for human vision, they reveal some striking properties of the foveal region of the human eye.

As I wrote in my article, the visual cells of the human retina are not sensitive to polarized light. As early as 1869, however, Hermann von Helmholtz made the assumption that the yellow pigment overlying the receptors in the foveal region of the retina was dichroic and hence could act as a polarizer. Today it is generally agreed that the molecules of the yellow pigment are (at least to a certain extent) circumferentially oriented within the foveal region. Looking through a polarizer at a brightly lighted blue surface will therefore reveal a dark brush oriented at right angles to the direction of polarization. The reason is that the dichroic pigment preferentially absorbs blue light. The yellow brushes of the Maltese cross appear instead of the dark brushes when a white source of polarized light is viewed.

The preferential alignment of the yellow pigment molecules in the foveal region is only part of the story of Haidinger's brushes. As various workers have suggested, and as C. C. D. Shute of the University of Cambridge has shown, the birefringence of the collagen fibrils in the cornea influences the orientation of the brushes. By using retardation plates to observe the Maltese cross in his own visual field, Shute was able to determine the direction of alignment and the amount of birefringence of the collagen fibrils in his cornea. Thus Haidinger's "flying phantoms" have turned out to be useful tools for studying the optical properties of the human eye. They are far too faint and unreliable, however, to be able to serve for polarized-light navigation in man.

RÜDIGER WEHNER

Zoological Institute
University of Zurich
Zurich

Sirs:

In "The Geometry of Soap Films and Soap Bubbles," by Frederick J. Almgren, Jr., and Jean E. Taylor [SCIENTIFIC AMERICAN, July], the authors note that the first person to have investigated the subject systematically and formulated the governing rules was the 19th-century Belgian physicist Joseph A. F. Plateau. It is of interest that when Plateau did this work, with its painstaking experiments, he was blind.

The 11th (1910) edition of the *Encyclopaedia Britannica* states in its biographical article on Plateau that in 1829 (when Plateau, who was born in 1801, would have been 28) "he imprudently gazed at the midday sun for 20 seconds, with the view of studying the after effects. The result was blindness for some days." He recovered, but then his sight gradually deteriorated over a period of

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14 years, "and in 1843 he became permanently blind."

"This calamity," the *Encyclopaedia Britannica* article continues, "did not interrupt his scientific activity," which he carried on with the help of others, including his wife, his son and his son-in-law, up to the time of his death, aged 82, in 1883. Plateau "direct[ed] the course of the experiments which they made for him, and interpret[ed] the bearing of the results."

"Even more extraordinary," the article observes, "were this blind man's investigations about molecular forces [including the soap-bubble forms], embracing hundreds of novel experiments whose results he saw only with others' eyes. These form the subject of his great work *Statique expérimentale et théorique des liquides soumis aux seules forces moléculaires* (1873), a valuable contribution to our knowledge of capillary phenomena."

The photographs by Fritz Goro accompanying the Almgren-Taylor article graphically emphasize the complexities of the subject matter with which Plateau labored, not only without the aid of modern knowledge and techniques but also lacking the most fundamental of all aids, sight.

KENYON J. ROBERTS

Los Angeles Journal of Commerce
and Independent Review
Los Angeles, Calif.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

NOVEMBER, 1926: "We now know that every atom is a complex structure, consisting of a positive electric charge of known amount and a definite number of negatively charged electrons arranged around the positive charge. The remarkable definiteness of the spectrum of each kind of atom at once suggests something very definite in the structure or behavior of the atom. These 'somethings' are the 'states' of the atom, and experiments show that light is emitted or absorbed by the atom only as it changes its internal structure from one of the states to another. The state of least energy, which we can take as the zero energy state, is the 'normal' state of the atom, that is, the state at which all the atoms are found unless some source of energy is acting to increase their energy to that of the other states, which are called 'excited' states. The differences between states are known to be due to differences in the arrangement of the electrons outside the nucleus, probably in the shape and size of their elliptical orbits. Every change of an atom from a state of higher energy to a state of lower energy is accompanied by the emission of light whose vibration frequency (the reciprocal of the wavelength) is directly proportional to the difference in energy between the two states. Thus if W_2 and W_1 are the energies of the two states, the change from state 2 to state 1 gives rise to the emission of light of frequency ν given by $W_2 - W_1 = h\nu$, where h is known as Planck's constant."

"Wings with slots at the leading edge and slotted rear flaps are now being used in at least four aircraft in England and Germany. In the trials of the Handley Page 'Hendon,' a torpedo-carrying plane equipped with these devices, some surprisingly slow-speed landings and glides on a steep path with the fuselage almost horizontal were recently made. In this aircraft when the front slot is open, the slotted rear flap is depressed. The lift coefficient of the wing is thereby increased between 75 and 100 per cent over its normal maximum value. The landing speed can be reduced correspondingly, adding appreciably to the safety of the craft. The particular advantage of this device, besides increasing the lift, lies in the fact that the ailerons continue to be effective when the wing is at a large angle of incidence beyond the 'burble,' or stalling, point; con-

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ventional ailerons beyond the stall become ineffective and produce a dangerous tendency to turn the machine in a direction that does not correspond with the desired bank."

"One of the first hospitals in this country to depart from the customary white operating room is St. Luke's Hospital in San Francisco. When the new hospital was constructed, the floor and wainscot of one of its operating rooms were finished in green tile. This was the idea of the chief surgeon, who called attention to the fact that the particular shade of green is the complementary color to 'blood' red. In this fact is to be found the reason for departing from the conventional white as an environment for the surgeon. Its dazzling brightness is blinding to the surgeon's eyes when he raises them from an operating field where the predominating color is red. Complementary colors afford the greatest eye relief, and dark green proves to be the most efficient in combatting the color fatigue to which the surgeon is subjected. In addition to lessening color fatigue complementary colors also intensify their opposites. Thus the operating field stands out more clearly in the surgeon's vision after he gazes for a moment at green."

"The decision of Judge Thompson of the Federal District Court in holding Lee De Forest to be the first and original inventor of the feed-back circuit and the oscillating audion will have a far-reaching effect in the radio industry. Twelve of the claims of the celebrated Patent No. 1,113,149, issued to Edwin H. Armstrong, are held to be invalid."

SCIENTIFIC AMERICAN

NOVEMBER, 1876: "The Centennial Exposition has closed, and so our grand celebration passes into the history of the country. That the Centennial has been successful beyond all previous world's fairs is plainly evident. The exhibits collectively were splendid representations of the resources and skill of the contributing nations. What a magnificent proof of the efficiency of our railroads to be able to point to the fact that eight million people were transported to Philadelphia from every portion of the country, and that there was but one casualty in which life was lost! Eleven years ago these eight million people were engaged in a bitter internecine war. Now great national gatherings take place month after month, unmarred by sectional strife or ill feeling. For three years the nation has been suffering from a shrinkage of values and a final stress that has brought ruin to thousands, and from whose evil effects no one has es-

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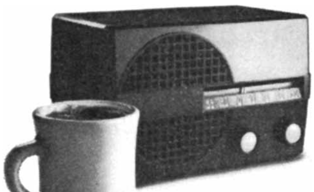
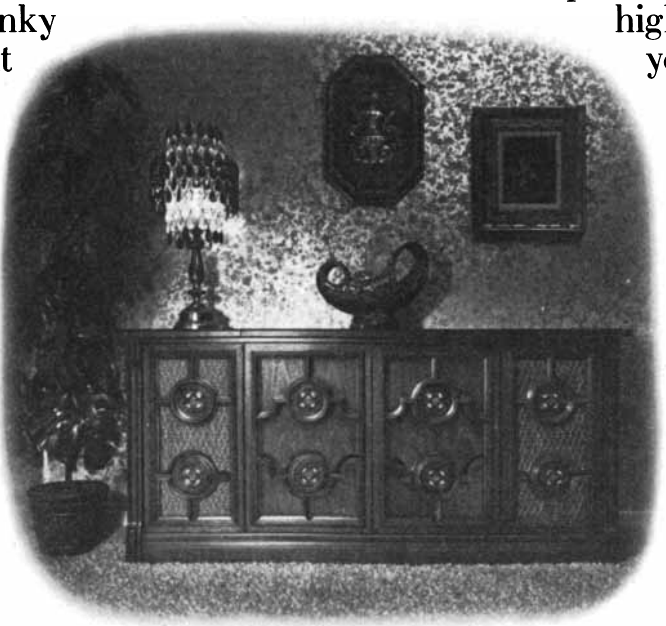


Good for news. Bad at music.

It's also a pleasure that 8 out of 10 Americans have never experienced.

Unfortunately, most people still listen to music played through dinky kitchen radios that weren't intended for accurate music reproduction in the first place.

Or they invest in "magnificent mediterranean fruitwood stereo consoles" which may be easy on the eyes but are generally a blight on the ears.



The $900 worth of fruitwood looks good. The $200 worth of electronics sounds bad.

Some people pick up nifty all-in-one stereo compacts they believe will give them good, high-fidelity sound. But a visit to a reputable high-fidelity dealer will quickly shatter that belief. Because only there will you hear *true* high fidelity and come to realize just how inadequate everything else is.

The simple truth is that only real high fidelity will give you real high-fidelity sound. That means separate component pieces; receivers, turntables, tape decks and speakers, each designed to do its job perfectly.

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Avoid buying cheap "no-name" stereo in a place like this or you'll end up with no-quality sound.

high-fidelity components than anybody. In fact, we're the leading high-fidelity manufacturer in the world today.

If you don't own some Pioneer components, or some of similar quality (such as that made by Marantz, Kenwood, Sansui and a handful of other dedicated companies) you're probably listening to bad sound. And it's so unnecessary. Today, in 1976, good hi-fi

This may be stereo. But it's not high fidelity.

components (as opposed to bad "no-name" stereo systems which are ridiculously low-priced and provide sound to match) cost no more than many unsatisfactory alternatives.

True, you can assemble a super Pioneer system that costs more than an automobile. But that's equipment designed for the high-fidelity purist to whom expense is no object.

On the other hand, the Pioneer receiver, turntable and speakers shown here cost about the same as the console pictured at left. And when it comes to sound, there's no comparison.

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You see, bad sound is not only unnecessary. It's unjustifiable.

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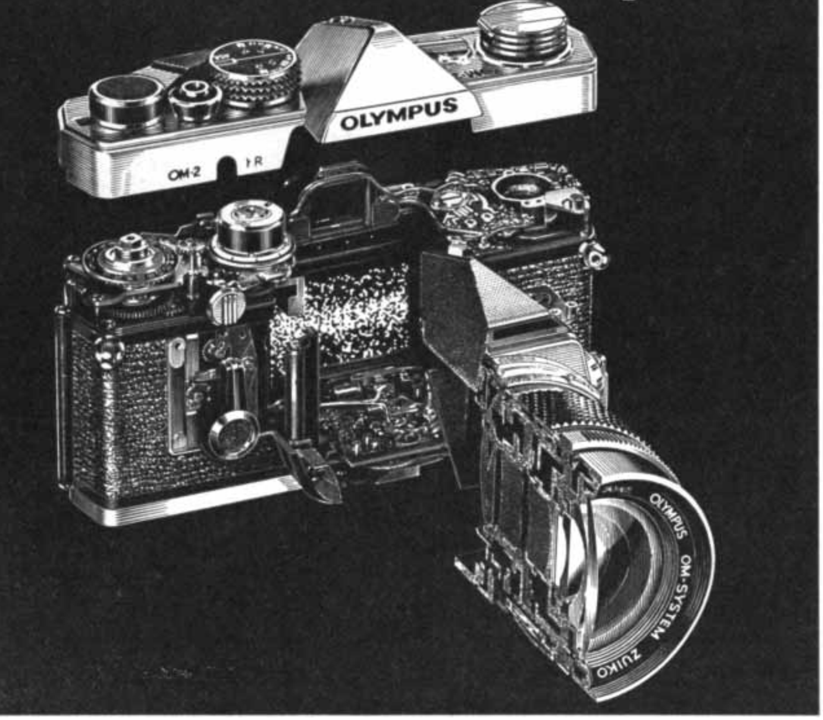

caped. Yet in the midst of these privations a vast national enterprise not only has been successfully carried through but also has included such a representation of the fruits of American industry as has never before been seen. In extended commerce due to the closer intercourse with other nations, in the consequent impetus to our industries and educational system, and in a broader cosmopolitan spirit diffused over the entire country, we look for the best results yet to be gained from the Centennial Exposition."

"Cellulose prepared from wood is now made for paper manufacturers in very large quantities. As far back as 1868 a company made paper from this material alone, without the addition of rags. Three years afterward five large mills were started (by an English company) in Sweden, and in Germany at the present time there are six factories in which the same process is carried out. It is somewhat as follows: the wood of pine and fir trees (oak is of no use what ever) is cut into small pieces a little less than an inch long by half an inch wide and a third of an inch thick, which are comminuted by passing them into a machine very like a large coffee mill. The wood is then boiled, under a pressure of 10 atmospheres, in a solution of caustic soda for about four hours. The residue is well washed, bleached, pressed and lastly dried and cut up into sizes suitable for packing."

"We have taken pains to enquire into a good many cases of alleged spiritual manifestation of the objective sort, and have failed to discover anything to justify the spiritual hypothesis. Every case that has been subjected to real scrutiny has been demonstrated to be a more or less clever fraud, abetted by a positive delusion on the part of the receivers of it, and the probability is overwhelming that the untested cases—if there are any—are of like character. Here is where we differ from those who used to dispute the theory of gravitation, including the great German poet and philosopher Goethe. They disputed, or willfully remained in ignorance of, an enormous mass of evidence verifiable by instrumental and mathematical means, evidence that could be verified every time by believers, unbelievers and the indifferent alike, evidence too that no other theory so easily, simply and completely satisfied. We, on the other hand, refuse to accept the spiritualist interpretation of a mass of facts, so called, most of which have been proved fraudulent or delusive over and over again; while for the small residue of fact that may be verified the spiritualist hypothesis is inadequate, inconsistent with the rest of our knowledge and enormously difficult of comprehension."

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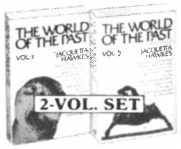

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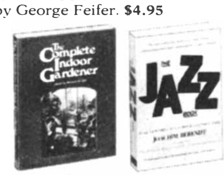

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THE AUTHORS

SIDNEY D. DRELL and FRANK VON HIPPEL ("Limited Nuclear War") are respectively physicists at Stanford University and Princeton University. Drell is professor, deputy director and executive head of the department of theoretical physics at the Stanford Linear Accelerator Center. He is also chairman of the High Energy Physics Advisory Panel of the Energy Research and Development Administration (ERDA) and a consultant for the Office of Technology Assessment (OTA), the National Security Council and the Arms Control and Disarmament Agency. He has been at Stanford since 1956, seven years after he received his Ph.D. in physics from the University of Illinois. Von Hippel is research scientist at the Princeton Center for Environmental Studies. After receiving his doctorate from the University of Oxford in 1962 he became a research associate at the Fermi Institute at the University of Chicago. Later he was a member of the physics department at Cornell University and at Stanford, and he has worked at the Lawrence Radiation Laboratory of the University of California and in the High Energy Physics Division of the Argonne National Laboratory. Drell and von Hippel came to collaborate on their article through their association with the Office of Technology Assessment. Von Hippel worked with the staff of the OTA on the original calculations on the effects of limited nuclear warfare. Drell also worked with the OTA staff, and he testified on limited nuclear warfare before the Senate Committee on Foreign Relations.

T. G. R. BOWER ("Repetitive Processes in Child Development") is currently visiting professor of psychology at the Free University of Brussels. He was graduated from the University of Edinburgh in 1963 and received his Ph.D. from Cornell University in 1965. For four years he worked at Harvard University on problems of perception, ontogenetic and phylogenetic development, and animal behavior. In 1969 he returned to Edinburgh to become lecturer in the department of psychology. In 1974 and 1975 he was a fellow at the Center for Advanced Study in the Behavioral Sciences in Palo Alto, Calif.

YOICHIRO NAMBU ("The Confinement of Quarks") is chairman of the department of physics at the University of Chicago. Born in Japan, he received both his undergraduate and graduate degrees in physics from the University of Tokyo. In 1952 he was invited to the Institute for Advanced Study in Princeton. "It was a turning point in my life," he writes, "because I have been in this country ever since." He spent two years at the institute before joining the faculty at Chicago. In 1971 he was elected to the National Academy of Sciences.

D. P. McKENZIE and FRANK RICHTER ("Convection Currents in the Earth's Mantle") are respectively geophysicists at the University of Cambridge and the University of Chicago. McKenzie is assistant director of research in the department of geodesy and geophysics at Cambridge. Since receiving his Ph.D. from Cambridge he has spent substantial periods at the Scripps Institute of Oceanography, the California Institute of Technology, the Massachusetts Institute of Technology and the Woods Hole Oceanographic Institution. This year he was elected a Fellow of the Royal Society. Richter is assistant professor of geophysics at Chicago, where he received his Ph.D. in 1972. For the next two years he was a research associate at M.I.T. During the 1974–1975 academic year he was a Guggenheim Fellow; he spent the year in the Cambridge department of geodesy and geophysics before joining the faculty at Chicago.

MITCHELL GLICKSTEIN and ALAN R. GIBSON ("Visual Cells in the Pons of the Brain") are at the Walter S. Hunter Laboratory of Psychology at Brown University. Glickstein is professor of psychology at Brown and a senior visiting research fellow in the department of physiology at the University of Oxford. After receiving his Ph.D. in psychology from the University of Chicago he worked at the California Institute of Technology and Stanford University. Before joining the faculty at Brown in 1967 he was associate professor at the University of Washington School of Medicine, holding a joint appointment in the departments of physiology and anatomy. "My principal interest is neural science," he writes, "particularly the structure and the function of the brain as they relate to the control of visually guided movement." Gibson is working on a postdoctoral traineeship at Brown. He went to Brown after receiving his Ph.D. from New York University.

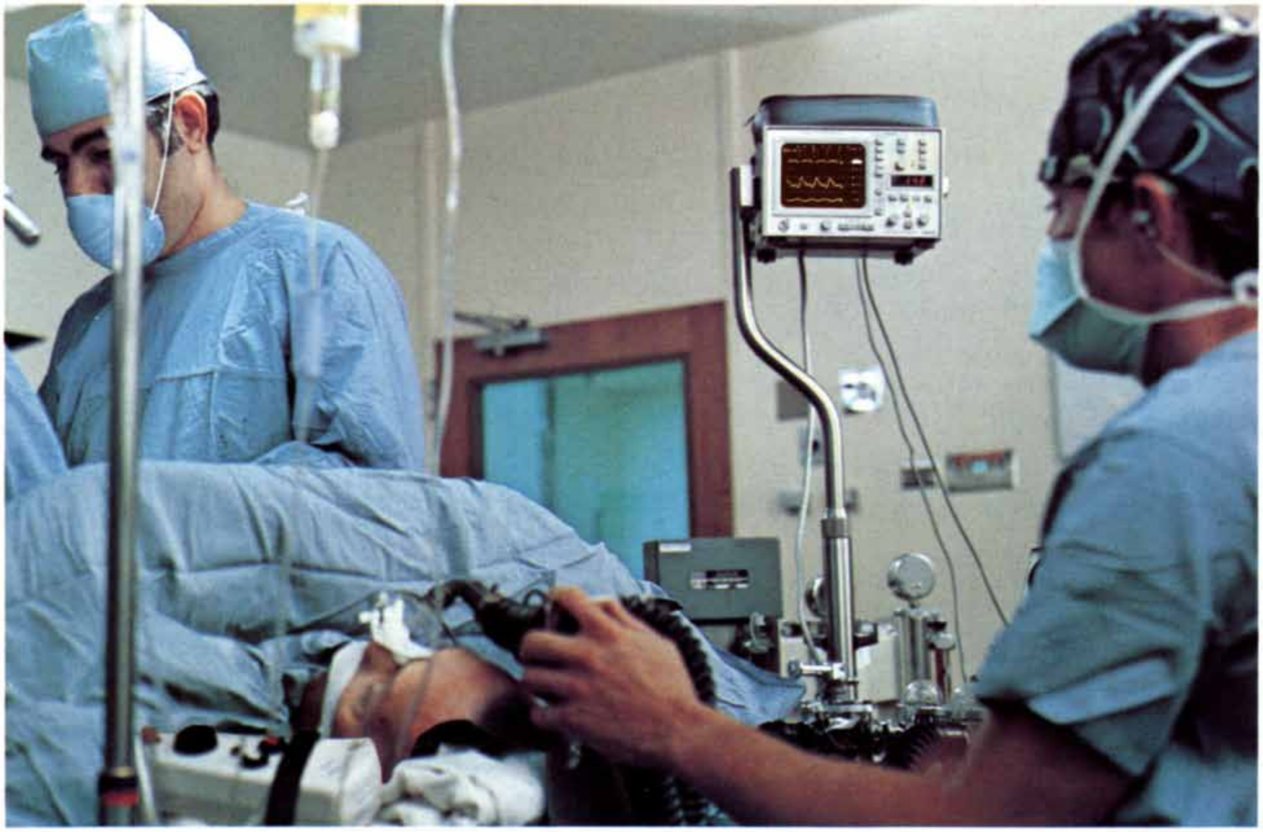
S. S. HECKER and A. K. GHOSH ("The Forming of Sheet Metal") are respectively metallurgists at the Los Alamos Scientific Laboratory and the Science Center of the Rockwell International Corporation. They met at the Research Laboratories of the General Motors Corporation, where they were doing the work on which much of their article is based. Hecker worked at the General Motors Laboratories from 1970 through 1973. Since that time he has been doing research at Los Alamos that he hopes will "lead to a better appreciation of materials problems in nuclear and new energy ventures." Ghosh joined the Physics Department at the General Motors Laboratories in 1972 after receiving his Ph.D. in metallurgy and materials science from the Massachusetts Institute of Technology. Before coming to the U.S. from his native India, he was graduated in 1966 from the engineering school of the University of Calcutta.

THOMAS S. ELIAS and HOWARD S. IRWIN ("Urban Trees") are respectively the assistant director of the Cary Arboretum of the New York Botanical Garden and the executive director of the New York Botanical Garden. Elias received his bachelor's and master's degrees at Southern Illinois University, majoring in botany and minoring in zoology. He was awarded his Ph.D. at Saint Louis University and the Missouri Botanical Garden. Before joining the Cary Arboretum he was assistant curator of the Arnold Arboretum of Harvard University and an extension lecturer. His main interests are trees and shrubs, and at the New York Botanical Garden he has developed a program for the study of shade trees and street trees. Irwin joined the Botanical Garden as a research associate in 1960 after receiving his Ph.D. in botany from the University of Texas. He became associate curator of the Botanical Garden in 1963, curator and herbarium administrator in 1966, head curator in 1968 and executive director in 1971.

JAMES A. TUCK and ROBERT J. McGHEE ("An Archaic Indian Burial Mound in Labrador") are anthropologists at the Memorial University of Newfoundland. Tuck is professor of archaeology at Memorial University, where he has been since 1968, when he received his Ph.D. from Syracuse University. For the past eight years he has been doing archaeological work in the northeastern U.S. and in eastern Canada, principally in Newfoundland and Labrador. During the academic year 1975–1976 he was on sabbatical leave sponsored by the Canada Council and Memorial University. He is currently excavating a stratified Indian and Paleo-Eskimo site on the northern peninsula of Newfoundland. McGhee received his undergraduate education at the University of Toronto and was awarded his Ph.D. by the University of Calgary in 1968. After graduation he accepted the position of Arctic archaeologist at the Museum of Man of the National Museums of Canada. In 1971 he joined the anthropology department of Memorial University, where he remained for five years. This year he returned to the Museum of Man to become High Arctic Archaeologist.

"A lot of advances in surgery have been made possible by better anesthesia - better trained personnel - better monitoring equipment"

Dr. Casey Blitt
University of Arizona, Health Sciences Center, Tucson



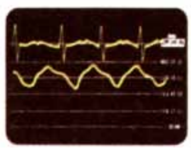
Anesthesiologist Dr. Casey Blitt, right, administers anesthesia for Surgeon Dr. Charles Witte at the Health Sciences Center, Tucson. Technological advances in physiological monitoring equipment, like this Tektronix monitor, have helped doctors to increase their standards of patient care. That's what monitoring is all about.

Dr. Casey Blitt recalls that as recently as ten years ago "if you were doing open-heart surgery, you had a huge, $10,000 to $20,000 monitor that was about the size of a door with a screen the size of a postage stamp, and you were lucky if you saw the trace at all. If you needed a monitor for a second patient, you were out of luck."

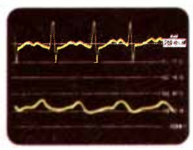
Tektronix has responded to the need for physiological monitors that are smaller, easier to read, offer multiple functions, have hard-copy capabilities, are reliable, and priced to allow widespread usage.

"In Tucson at the present time, and in a lot of cities that I know of," comments Dr. Blitt, "continuous electrocardiogram monitoring of every patient in the operating room is now the anesthesiology standard of care." Dr. Blitt uses a monitor even during routine operations, like hernias and gall bladders, because he doesn't want to miss critical information. "There are trends that can be followed, and followed more easily with a continuous monitoring device."

The big operations — open-heart cases, big vascular cases, neurosurgical cases, kidney transplants—would not be possible without the advances in anesthesia, in the training of anesthesiologists, and in monitoring equipment. The problem is not always that the surgical procedure is so technically difficult in itself. The surgeon must have confidence in the anesthesiologist's ability to keep the patient alive during the trauma of surgery. One neurosurgical operation in San Diego, for example, went on for an incredible 33 hours. People are being given new leases on productive lives. This is modern medicine.



A flotation catheter entering the right atrium produces this characteristic waveform on the monitor's screen.*



Now the doctor knows that the catheter has floated on, and is entering the pulmonary artery.

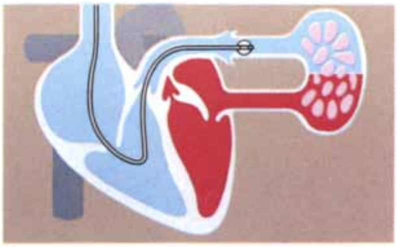
*Expanded scale

What a doctor sees

The upper waveform is the electrocardiogram (heart rhythm), an electrical signal generated by the heart. The lower waveform is a pressure trace, produced in this case by the flotation catheter. Dual pressure traces on the Tektronix 414FA being used by Dr. Blitt yield even more critical information. He can also select a digital readout of heart rate (derived from the ECG trace), systolic or diastolic blood pressure (from the peaks and valleys of the pressure trace), mean blood pressure, or temperature.

Tektronix' physiological monitors

evolved from its oscilloscope technology. What you see on an oscilloscope screen is the graph of some electrical event, or any of a variety of phenomena that can be converted to electrical signals—heat, sound, pressure, strain, velocity, nuclear events, acceleration, biomedical signals....



Making the big operations possible. Doctors think of the heart as two organs, or two pumps, right and left. Both can fail independently. Since it's often extremely important to know which is failing, both sides must be monitored.

Pulmonary artery catheterization, commonly called "the Swan-Ganz technique," is one answer to a safe way to monitor the left side of the heart —from the right side, rather than entering from the left, which has always been more invasive. A balloon-tipped, flotation catheter is inserted into a large vein, such as the internal jugular in the neck, and advanced into the right side of the heart, traversing the right ventricle, and then advanced into the pulmonary artery. The inflated balloon lodges in a vessel smaller than its own diameter. The resulting "wedge" pressure allows the doctor to monitor the integrity of the left side of the heart.

Continuous pressure-waveform display is mandatory when inserting a pulmonary artery catheter.

More than an operating room need. Compact monitoring units that clearly displayed pressure waves changed medical practices and improved patient care. Now there are monitors in recovery rooms, intensive-care units, and they're used in transport situations, including in-hospital transport.

In moving patients from room to room, floor to floor, up and down ramps, vital signs can be monitored second by second. It's the early warning system that might make a critical difference in patient care.

The trend in monitoring appears to be away from large, centralized systems. The concern is the cost of the failure of the whole system. Many hospitals are working toward each room being able to stand on its own.

Lower monitor prices make it possible for smaller hospitals to expand their health care capabilities. Dr. Blitt points out that "there are an awful lot of rural and community hospitals that have a need for intensive-care capabilities." Even if it's only to stabilize the patient's condition before transport to a major medical center.

Tektronix has been working to remove the cost barriers to the even wider use of superior patient monitors. For example, the new Tektronix 414 Portable Patient Monitor, shown below, is priced at $2,700, sometimes enabling a hospital to have four monitors for the price of a competitive unit with comparable features.

The optional 400 Series Recorder attaches directly to the monitor and provides permanent, paper-strip copies of monitored data.

These are just two of the over 835 Tektronix products serving the test, measurement, and information display needs of customers worldwide. For additional information about our medical products, contact Reagh Stubbs, Medical Products Marketing Manager, Tektronix, Inc., P. O. Box 500, Beaverton, Oregon 97077. By phone — call free by using our Medical Products WATS line 800-547-4804.

Newborn babies in trouble are transported from outlying hospitals by medical personnel trained by Neonatologist Dr. Tom Harris, Tucson. Neonatology is a pediatric subspecialty. Nationwide, regionalization of newborn care has dramatically increased the need for transport services. Dr. Harris and his staff depend heavily upon physiological monitors for continuous information about the vital signs—a newborn baby's condition can deteriorate extremely fast. The battery-operation feature of the Tektronix 414 monitor can be a lifesaver in transport situations.

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Limited Nuclear War

The U.S. may be committing itself to preparing for a war limited to attacks on military bases, with relatively few civilian casualties. Would the casualties really be few, and could the war stay limited?

by Sidney D. Drell and Frank von Hippel

For more than a decade U.S. strategic policy has been dominated by the recognition and acceptance of a few simple facts: We and the Russians are each other's nuclear hostages; in the event of nuclear war neither this country nor the U.S.S.R. would be able to defend itself against virtual annihilation; even if one side were to initiate the war with a massive preemptive attack, the other would retain an "assured destruction" capability, the ability to devastate the attacker. In one form or another this recognition has underlain most of the past quarter century of mutual deterrence.

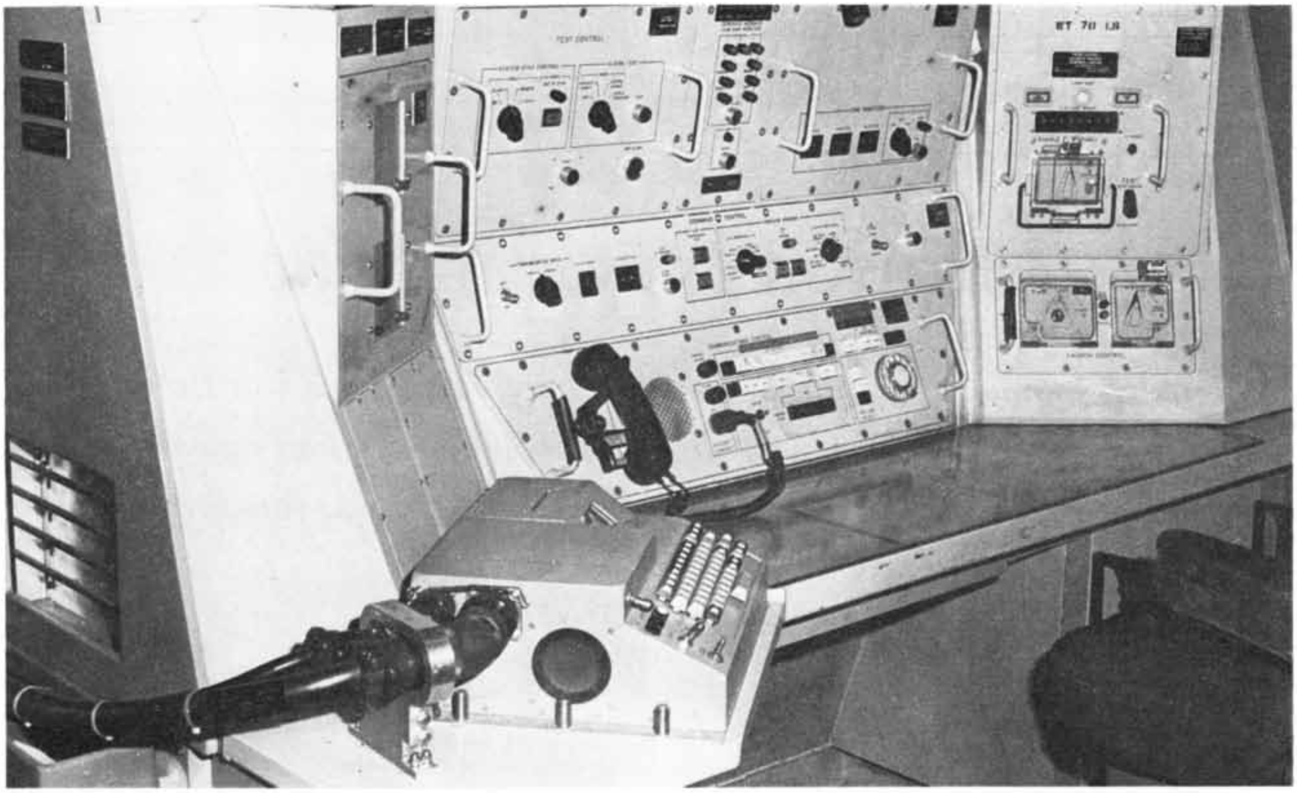
It has also been recognized, however, that nuclear weapons might be launched with restraint on both sides, with less than devastating results. President Nixon emphasized in 1970 the importance of having options other than "massive retaliation" for replying to a small (and possibly accidental) attack. That formulation of flexible response was nothing new. U.S. leaders have for many years had the option of launching a limited nuclear attack rather than an all-out one. The requirements of flexible response were expanded, however, by former Secretary of Defense James R. Schlesinger in Congressional testimony on March 4, 1974. According to his formulation, the U.S. should include in its flexible-response repertory the possibility of replying to a limited nuclear attack with selected strikes, notably "counterforce" strikes targeted against enemy military installations. Schlesinger argued that such strikes would be qualitatively different from intentional attacks on population centers, reducing the probability that a limited nuclear war would escalate into a massive exchange resulting in large civilian casualties, and that a flexible capability would make the possibility of a U.S. nuclear attack more credible and would thus increase the leverage provided by U.S. nuclear forces in international confrontations.

Since 1974 Schlesinger and other defense spokesmen have emphasized what they now seem to regard as two necessary new ingredients of a flexible-response strategy. One is the development of intercontinental ballistic missiles (ICBM's) capable of destroying "hardened" Russian military targets, such as missiles emplaced in blast-resistant underground silos. The other is a major expansion of the civil defense program, which has been largely inactive since the early 1960's. The purpose of the civil defense program would be to improve the credibility of the U.S. limited-nuclear-war posture by protecting the civilian population from the effects of limited Russian nuclear attacks. The new emphases give more weight to achieving a capability for fighting and "winning" a limited nuclear war.

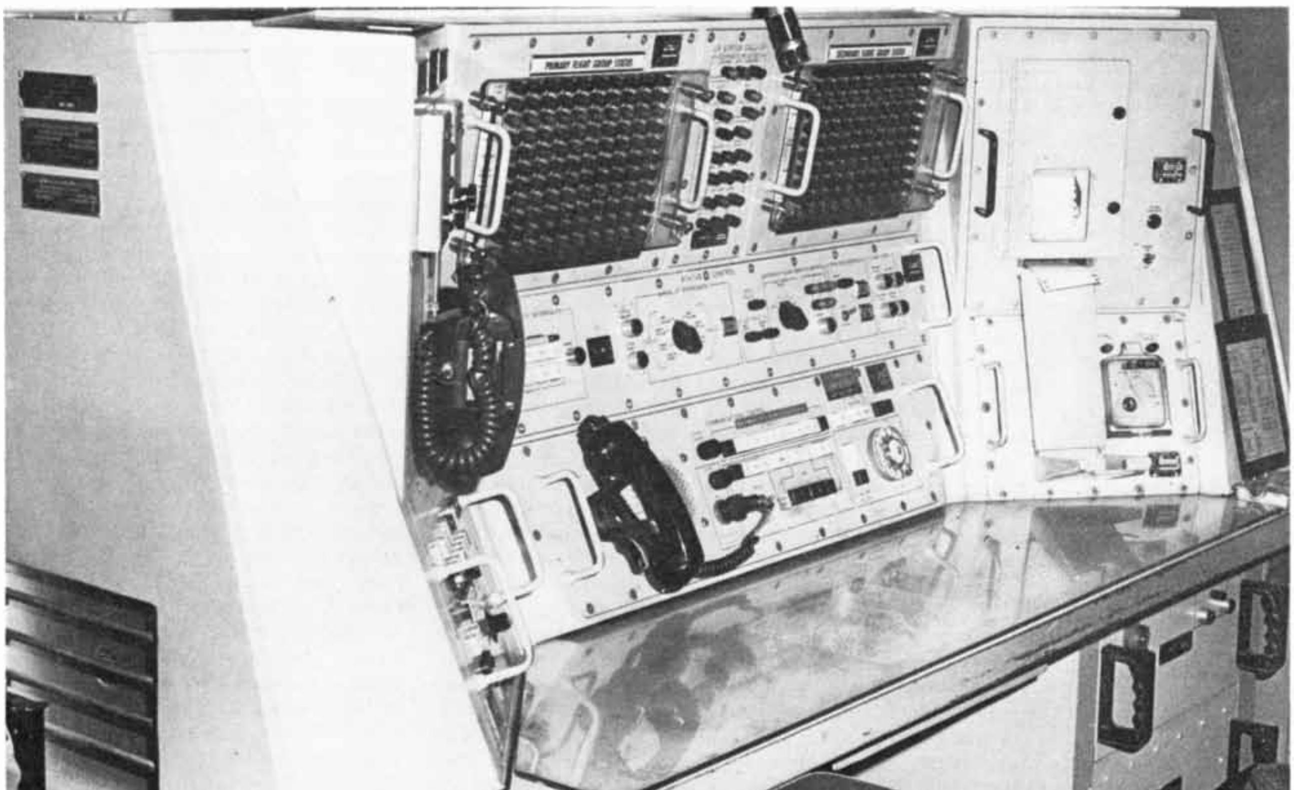
This proposed shift in strategy and the weapons-development and civil defense measures being sought to support it have come under attack on two broad grounds. First, detailed calculations based on the properties of nuclear weapons of the coming decade suggest that the casualties from any militarily significant nuclear counterforce strike would be so devastatingly high that this concept of limited nuclear war loses meaning. Second, a counterforce strategy founded on the ability to destroy enemy ICBM's increases the chances of nuclear war.

In his testimony before a subcommittee of the Senate Committee on Foreign Relations in March, 1974, Schlesinger supported his advocacy of such a counterforce capability by suggesting that a counterforce strike against the U.S. might result in "hundreds of thousands" of civilian casualties "as opposed to tens and hundreds of millions," which could result from an all-out nuclear exchange. Several senators were skeptical that a militarily significant strike could cause so few casualties; Senator Clifford P. Case of New Jersey in particular asked that the basis for the casualty calculations be further explained. In September, Schlesinger returned with Department of Defense computer calculations on the consequences of limited nuclear war. The figures indicated that if extensive civil defense protection were available and taken advantage of, a Russian attack on all 1,054 Minuteman and Titan ICBM's, with one one-megaton warhead targeted on each silo, would cause about 800,000 civilian deaths. Schlesinger concluded from this that "the likelihood of limited nuclear attacks cannot be challenged on the assumption that massive civilian fatalities and injuries would result."

Some senators were still skeptical, and the Congressional Office of Technology Assessment (OTA) was asked to review the Defense Department calculations. An expert panel including one of the present authors (Drell) reported back in February, 1975, that "the casualties calculated were substantially too low for the attacks in question as a result of a lack of attention to intermediate and long-term effects" of the nuclear explosions. Pointing out that the Russian strike postulated by the Defense Department was "evidently not designed to maximize destruction of U.S. ICBM's," the panel insisted that a real Russian effort to cause maximum damage to U.S.



MINUTEMAN III missile combat-crew commander's console controls the launching of a flight of 10 missiles. The keyboard (*foreground*) is that of the Command Data Buffer system, which makes possible the resetting of targets in on-board computers in 36 minutes.



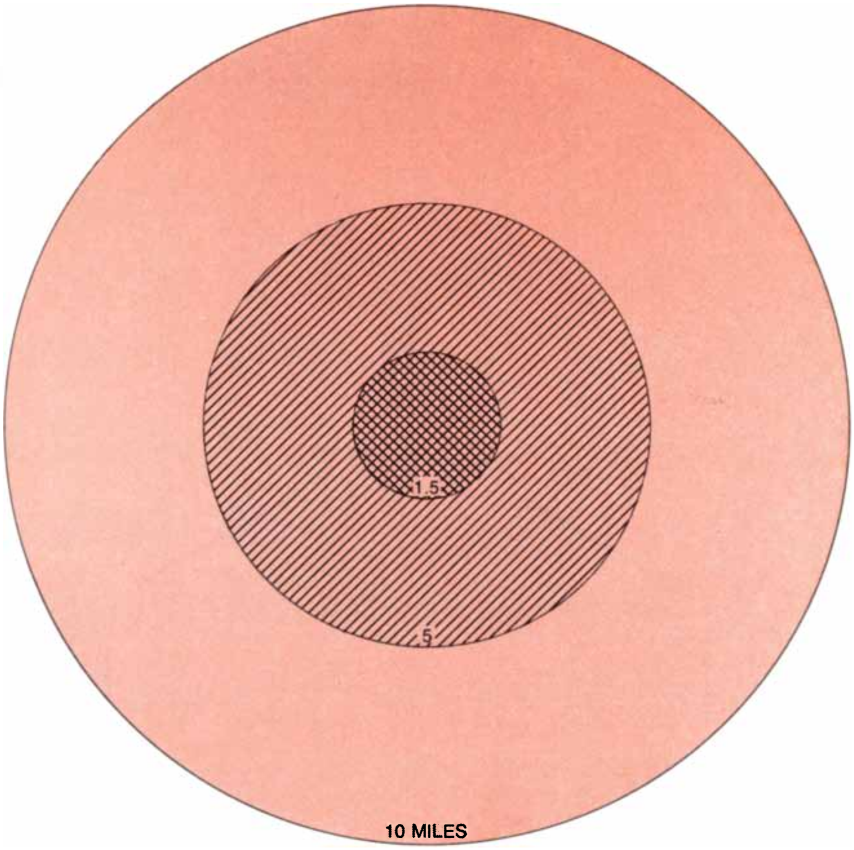
MINUTEMAN II console shown here is that of the deputy combat-crew commander. The consoles are in underground launch-control centers. The U.S. has 450 Minuteman II's and 550 Minuteman III's, the latter with multiple independently targetable reentry vehicles.

strategic forces with weapons currently deployed or under development would in fact "inflict massive damage on U.S. society." The panel raised specific questions about some of the assumptions underlying the Defense Department's calculations, and it also asked for estimates of the probable degree of damage to U.S. military targets for postulated attacks. This is a critical point, since it would be specious and misleading to calculate a low casualty figure for some imagined trivial—and therefore unlikely—counterforce attack.

In response to the panel's critique Defense Department analysts tested the sensitivity of their calculations to the assumptions challenged by the panel and estimated the effectiveness of various possible Russian strikes. In what follows we shall consider these issues and some of the underlying technical factors. We shall draw in part on the Defense Department's results, which were reported in July, 1975, and also on an independent analysis, produced by Henry C. Kelly of the staff of the Office of Technology Assessment in collaboration with Richard L. Garwin and one of us (von Hippel), presented to the Committee on Foreign Relations that September. What emerges is this: Strikes causing relatively few casualties would be militarily insignificant; strikes inflicting appreciable damage on U.S. strategic forces would cause very large civilian casualties; even the most comprehensive counterforce attack that was postulated would leave the U.S. with such massive retaliatory capability as to make the counterforce strategy appear to be ineffective from the Russian point of view.

We begin by examining the techniques for calculating the civilian casualties resulting from a nuclear attack. Casualty levels depend sensitively on many factors, such as the nature of the attack, weather conditions and civil defense protection. The basic physics of warhead effects, however, is fairly well established and widely known; it is set forth most comprehensively in *The Effects of Nuclear Weapons,* a publication of the Department of Defense and the Atomic Energy Commission, edited by Samuel Glasstone, that was published originally in 1957 and in revised form in 1962.

For a low-altitude nuclear explosion releasing the energy equivalent of a million tons (one megaton) of TNT the immediate effects of blast, heat and nuclear radiation would extend over an area around ground zero with a radius of about 10 miles. At military targets near populated places, such as naval shipyards, missile-submarine bases and some command centers, the Defense Department calculated that blast fatalities alone would be between 50,000 and 100,000 per one-megaton warhead exploded high enough so that local radioactive fallout would not be a hazard. For military targets in places with a low population density, casualties from these immediate effects would be much lower. For such targets it is radioactive fallout that would account for most of the civilian casualties, and the fallout from a Russian attack on a Minuteman base could be lethal many hundreds of miles downwind. Considering the weapons that are deployed today or are likely

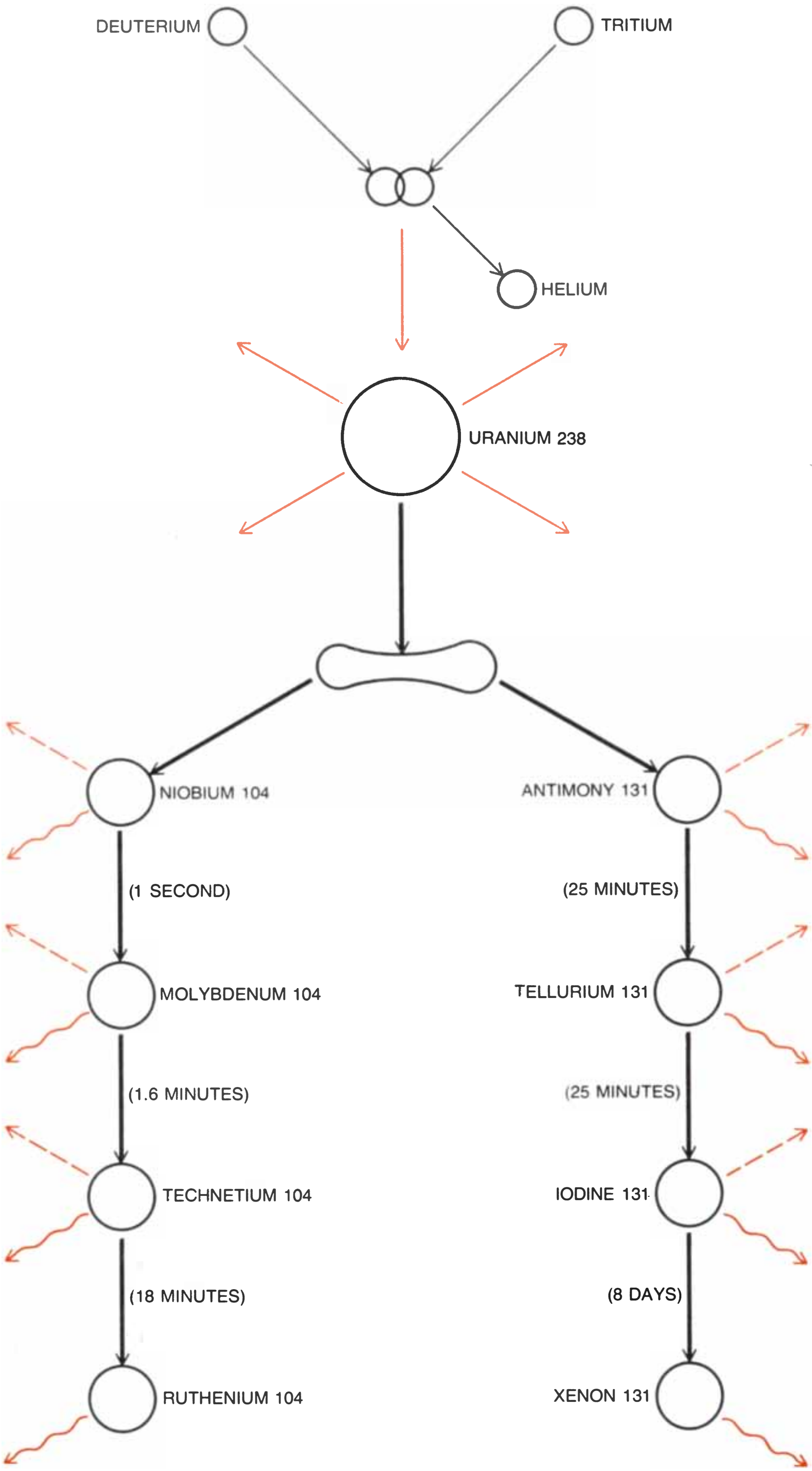


CAUSE		EFFECT
(thermal swatch)	THERMAL RADIATION	BURNS AND FIRES, POSSIBLE FIRESTORM
(blast swatch)	BLAST	CASUALTIES FROM BUILDING COLLAPSE AND FLYING GLASS
(nuclear swatch)	NUCLEAR RADIATION	RADIATION DEATHS

IMMEDIATE EFFECTS of a nuclear explosion are due to the initial nuclear radiation, the air blast and the thermal radiation. The approximate radii at which the various effects would be significant are given here for a one-megaton nuclear warhead exploded near the surface.

DOSE (IN REMS)		EFFECT
IF DELIVERED OVER ONE WEEK	IF DELIVERED OVER ONE MONTH	
150	200	THRESHOLD FOR RADIATION ILLNESS
250	350	5 PERCENT MAY DIE
450	600	50 PERCENT MAY DIE

BIOLOGICAL EFFECTS of nuclear radiation vary with the rate at which a dose is delivered. The dose unit, the rem, takes into account the relative effectiveness of the type of radiation.



FISSION PRODUCTS, the source of fallout radiation, are produced in the chain of events following a nuclear explosion, in this case a typical fission-fusion-fission explosion. Heated by an initial fission explosion, the hydrogen isotopes deuterium and tritium fuse to form helium, releasing an energetic neutron (*colored arrow*). The neutron enters the nucleus of a uranium-238 atom, making it unstable; it fissions, releasing four neutrons and two radioactive daughter nuclei, or fission products. The fission products emit beta rays, or electrons (*broken arrows*), and gamma rays (*wavy arrows*), thus decaying to form new products. Each decay chain ultimately terminates in a stable isotope. For each transition there is a characteristic half-life, which tends to become longer as the stable stage is approached. Other decay chains, not illustrated here, produce the important long-lived radioisotopes strontium 90 and cesium 137.

to become available in the next decade, such an attack might be delivered by one megaton or two megatons of nuclear explosive fuzed to detonate near the surface at each of the 150 or 200 hardened ICBM silos at the base.

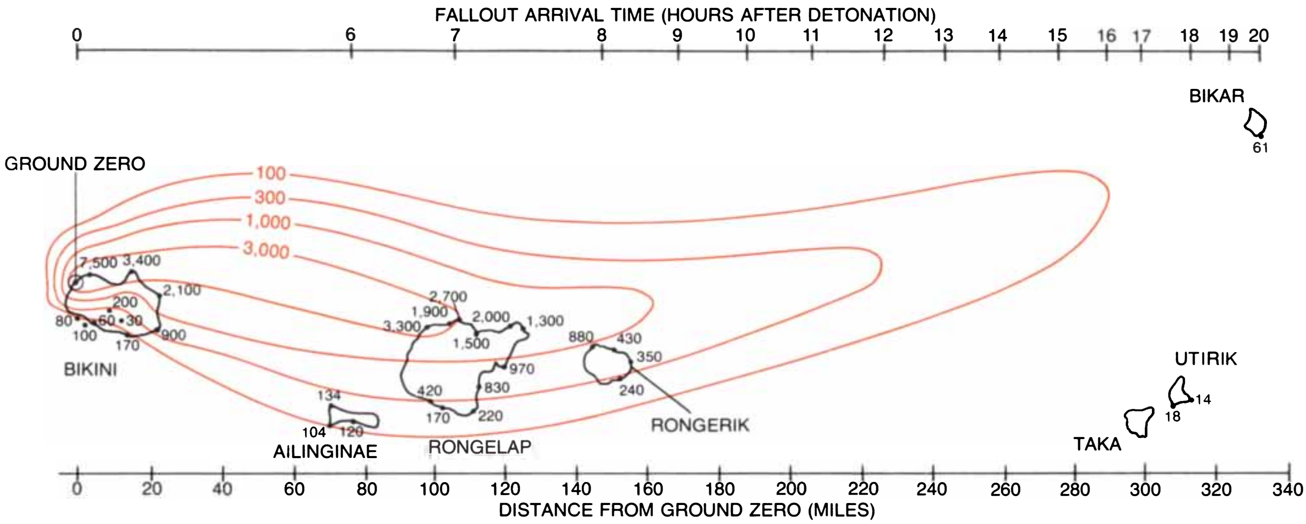
Radioactive fallout originates with the thousands of tons of soil, rock and other material that would be melted or vaporized by the heat of each explosion and mixed with its radioactive by-products. This debris would be carried to a height of some eight miles with the rising fireball. In the stratosphere the fireball would cool and the larger particles would descend to the ground within a day or so, over an area extending some hundreds of miles downwind, as "local" fallout. The smaller particles would drift great distances and eventually descend as global fallout.

The hazards of local fallout were dramatized by the events that followed the first U.S. test of a fission-fusion-fission bomb (with a yield of 15 megatons) at Bikini Atoll on March 1, 1954 [*see illustration on opposite page*]. Fishermen 80 miles downwind received radiation doses that ultimately killed one of them. At the south end of Rongelap Atoll, 100 miles downwind, people suffered severe short-term and long-term radiation effects. If they had been living at the north end of the atoll, the higher radiation levels there would almost surely have killed them.

If people in the local-fallout zone did not (as the residents of Rongelap did) ingest contaminated food and water, the principal hazard would be external radiation from radioactive particles. (Most of the particles in local fallout would be too large for inhalation into the lungs.) If people did not stay outdoors and come into direct contact with fallout, thereby sustaining burns caused by beta particles (the short-range electrons emitted by radioactive nuclei), the major hazard would be the more penetrating gamma radiation.

In order to determine the distribution and consequences of local fallout one needs to know the fission yield and height of burst of each warhead, the biological effects of a given absorbed radiation dose, the dependence of the fallout pattern on weather conditions, the degree to which the population is sheltered and the geographic distribution and total megatonnage of the attack. Predictions of fatalities and injuries are sensitive to the assumptions one makes about each of these factors, which we shall consider in turn.

The radioactivity in the fallout would come mostly from fission. A "thermonuclear" weapon is typically a fission-fusion-fission device. A "small" fission explosive (one of the chain-reacting isotopes uranium 235 or plutonium 239)



HAZARDS OF LOCAL FALLOUT downwind from a thermonuclear explosion were dramatized by the U.S. test of a 15-megaton fission-fusion-fission bomb on Bikini Atoll on March 1, 1954. The measurements (*black numbers*) give the total dose, in rems, that had accumulated 96 hours after the explosion. Contour lines calculated on the basis of those measurements outline the fallout pattern.

triggers a fusion explosion involving, for example, the hydrogen isotopes deuterium and tritium. The high-energy neutrons emitted by the fusion reactions then fission the nuclei of a large amount of the non-chain-reacting isotope uranium 238, releasing more fission energy [*see illustration on opposite page*]. In the Defense Department calculations 50 percent of the energy release was assumed to be due to fission, and that is a representative fraction.

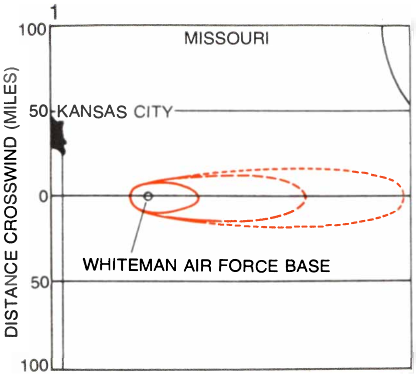
The biological consequences of gamma radiation depend on the total dose received and the time period over which it is delivered. The median lethal radiation dose was taken by Defense Department analysts to be 450 rems for doses received within a few days. (The rem, standing for "roentgen equivalent man," is a unit of the biological effect of radiation.) For doses delivered over a longer time the lethal dose was taken to be somewhat higher because, given time, a biological system can repair a considerable amount of radiation damage. The effective dose suffered by the exposed population when the rate of repair just balances the rate of damage being done by the decaying ambient field of radiation would be the "maximum biological dose" and would determine the lethality of the exposure.

Death from radiation sickness would be neither quick nor painless. As described in the Glasstone book, "the initial symptoms are . . . nausea, vomiting, diarrhea, loss of appetite and malaise." Beginning two or three weeks after the exposure "there is a tendency to bleed into various organs, and small hemorrhages under the skin . . . are observed." Spontaneous bleeding from the mouth and intestinal tract is common. "Loss of hair . . . also starts after about two weeks. . . . Ulceration about the lips may . . . spread from the mouth through the entire gastrointestinal tract." Eventually "the decrease in the white cells of the blood and injury to other immune mechanisms of the body . . . allow an overwhelming infection to develop." One has only to multiply that description by the millions to get a partial picture of the possible consequences of "limited" nuclear attacks on the U.S. and the U.S.S.R.

If the fresh fission products from one megaton of fission were spread uniformly over a perfectly flat area of 1,000 square miles, the gamma-ray dose rate one meter above the ground would be about 250 rems per hour after 10 hours. For human beings the median lethal dose at such a high dose rate is about 450 rems. The gamma-ray dose rate would decrease about sixteenfold for every tenfold increase in time for the first six months after the explosion and more rapidly thereafter. In our example the radiation intensity would be down to about 15 rems per hour after four days and about one rem per hour after 40 days. For a person remaining in the radiation zone, however, the cumulative dose would continue to rise significantly for quite a long time. Consider the local fallout beginning about 10 hours after an explosion, which is a typical time for the fallout to reach ground level. A full 40 percent of the dose accumulating after that time would remain to be delivered after four days, and 25 percent of it would still remain to be delivered after 40 days.

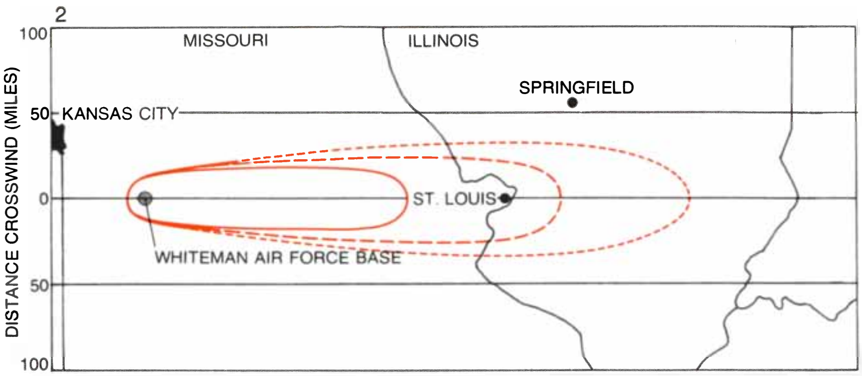
The height of burst of the warheads, which has an important influence on the amount of fallout deposited downwind, would be affected by the choice of target. In the counterforce attacks envisioned by the Defense Department most of the megatonnage would be directed against underground Minuteman silos. The Department reported that the Minuteman-killing effectiveness of surface bursts and of airbursts at the "optimum height of burst" would be about equal. (The optimum height of burst is the height that, for a given yield, provides a blast pressure exceeding a certain value over the largest area; for a one-megaton yield and an overpressure of 1,000 pounds per square inch it would be about 1,000 feet.) The attacker would thus be faced with a trade-off. On the one hand a surface burst does not have to be as precisely placed as an airburst (an important consideration, since attacks on hardened targets put a high priority on accuracy). On the other hand, Defense Department calculations show that, other things being equal, for an attack on the U.S. ICBM's fallout fatalities could be four times higher for surface bursts than for airbursts.

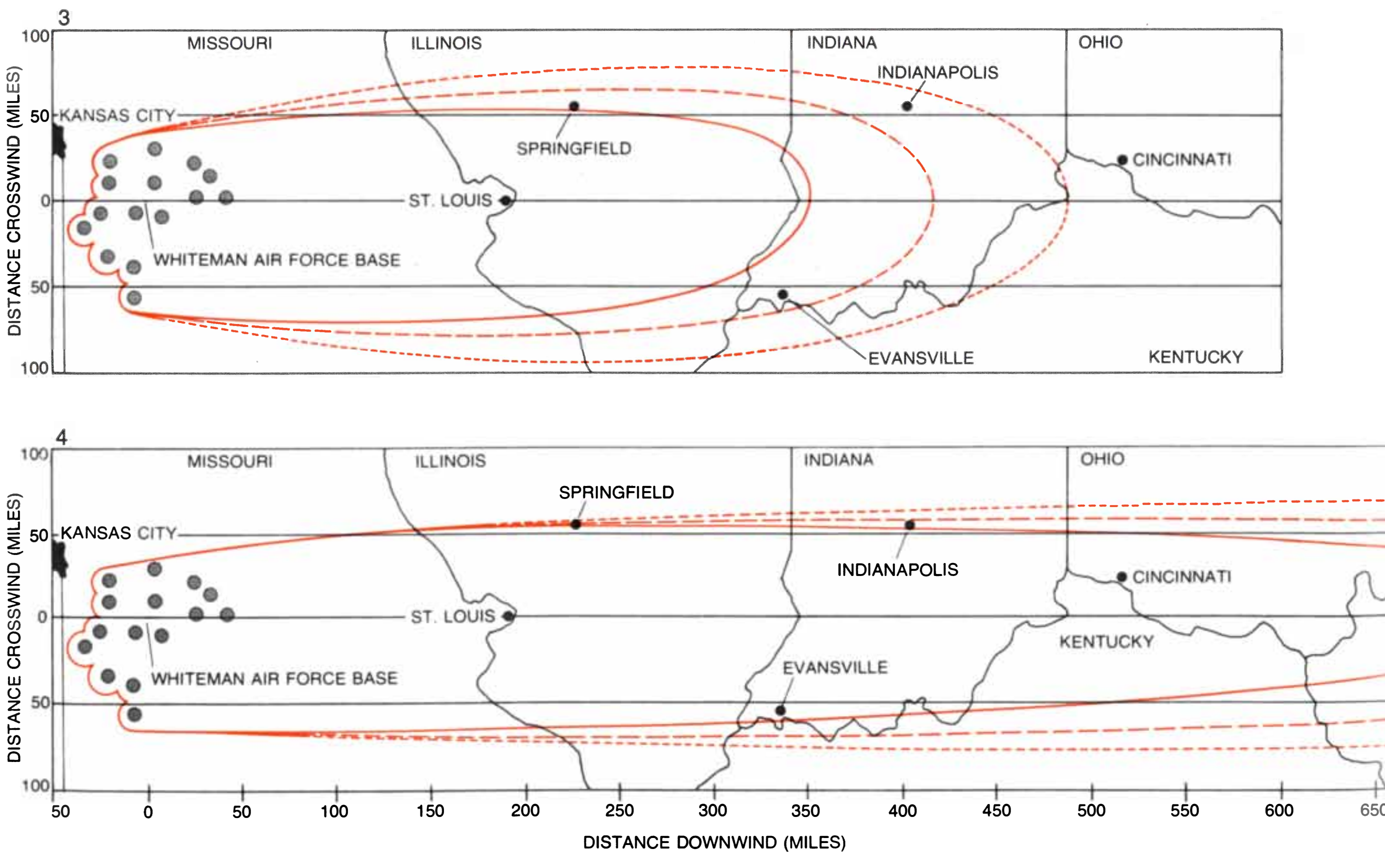
The fireball from a one-megaton nuclear explosion and the fission products it contains rise rapidly until the top of the cooling fireball cloud enters the stratosphere, about six miles above sea level at middle latitudes. At a height of about eight miles the cloud stabilizes, with its fission products spread over an area about four miles in diameter. An average settling time for the local fallout from a one-megaton explosion might be about eight hours. The settling time and the average speed of the winds between the top of the fireball cloud and the ground determine how far the particles drift downwind. For a typical aver-



age wind velocity of 20 miles per hour the average drifting distance would be 160 miles. (The settling time also determines the extent to which short-lived radioactive isotopes decay harmlessly before reaching the surface.) The width of the fallout pattern is determined primarily by the differences in the speed and direction of the winds to which particles are subjected at various heights in the cloud. For a typical wind shear of one mile per hour per mile of height and an average wind speed of 20 miles per hour, the pattern of fallout 100 miles downwind from ground zero would be about 25 miles wide.

Clearly the number of casualties depends to a considerable degree on what weather conditions are assumed. In the Defense Department calculations the total casualties from one postulated attack were three times higher with typical March winds blowing than they were with typical June winds. Such variations are largely due to changes in wind direction and wind speed that cause the fallout pattern to cover certain densely populated areas or miss them. Consider the fallout pattern downwind from the Minuteman wing at Whiteman Air Force Base in central Missouri after a Russian attack by two one-megaton surface bursts (with 50 percent of the yield from fission) on each of the base's 150 silos. With an average wind velocity of 20 miles per hour the lethal fallout zone for people indoors would stretch to the Illinois-Indiana border; with an average wind velocity of 60 miles per hour (which is not an unusual speed high in the troposphere, where the fallout would be for most of the time before it





FALLOUT PATTERNS are shown for attacks by one-megaton warheads (with 50 percent of their explosive yield from fission) exploded at the surface on ICBM's at Whiteman Air Force Base in Missouri. The contours correspond to maximum biological doses of 1,350 rems outdoors, or 450 rems (50 percent fatalities) inside an average residence (*solid line*); 450 rems outdoors (*broken line*), and 150 rems outdoors (*dotted line*), the approximate threshold for fatalities. The four patterns are for a single warhead (*1*), for one warhead

settled to the ground) it would stretch all the way to the Virginia border [*see illustration on these two pages*]. The area within the lethal-dose contour would be very large: about 2 percent of the land area of the continental U.S.

There are six Minuteman bases from which comparably massive fields of lethal radiation would extend, and three 18-missile Titan bases as well. Hence in the event of a counterforce strike against U.S. missiles a substantial portion of the U.S. would be covered by the downwind radiation patterns from the thousands of nuclear explosions. And a significant fraction of the population, including the residents of many major Middle Western cities, would be in the zones of lethal radiation [*see illustration on next page*]. Presumably a map of the U.S.S.R. would show a similar pattern for a U.S. counterforce attack on that country.

The consequences of being caught in the fallout pattern downwind from a low-altitude or surface fission explosion would depend, of course, not only on the level of ground contamination but also on where one took refuge. Currently the U.S. civil defense program requires that for a shelter space to be identified as such it must shield against all but 1 to 2 percent of the fallout gamma radiation. The degree of protection a given shelter provides is characterized by its "protection factor," which is the reciprocal of the fraction of radiation that penetrates it. The current requirement is therefore a protection factor of 50 to 100. That degree of shielding can be provided by cover of approximately two feet of dirt or 16 inches of concrete. Those parts of a single-story residence that are above ground level have a protection factor of 3. The basement of the residence may have a protection factor of 20 to 40 if it is completely below ground level and therefore receives gamma radiation almost entirely from fallout that lands on the roof of the building.

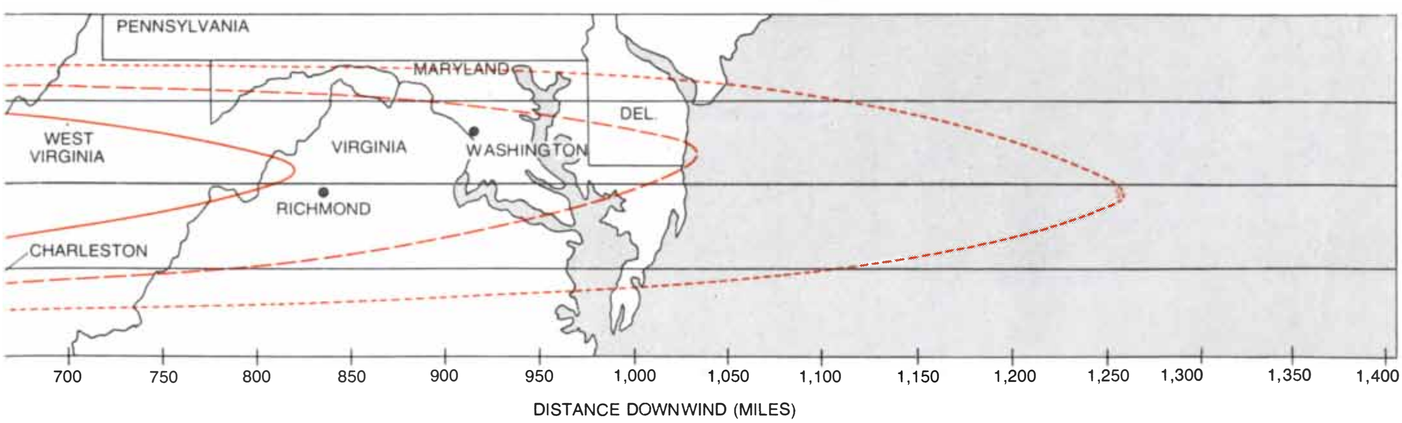
In the Defense Department calculations the postulated distribution of protection factors corresponds to assuming that about 60 percent of the people in the U.S. would seek and reach the best shelter available in their area [*see top illustration on page 35*]. The 40 percent who did not seek shelter or for whom shelter was not available were assigned a protection factor of 3, that of an average residence. It was found that halving the protection factors increased the number of deaths by more than 50 percent.

It is important to note that the Defense Department analysts assumed that people would remain sheltered for 30 days. At the current level of civil defense preparation it is highly unlikely that the population could remain so well sheltered for such a length of time. For a limited nuclear war to be taken seriously as a policy option—as a realistic threat in a confrontation with the U.S.S.R.—it would be necessary to make much better shelter arrangements. In other words, the U.S. would have to embark on a greatly enlarged civil defense program.

Indeed, the development of civil defense procedures requiring the massive evacuation and relocation of populations during crises has recently been proposed in the annual U.S. defense budget request as a necessary adjunct to the new strategy. The preparations required for such mass movements and for the support of the population for long periods away from home would have a major impact on U.S. peacetime society. Identified shelter spaces and evacuation plans by themselves would not constitute an effective civil defense program; a total system would have to be organized and woven into civilian life through training programs, rehearsals and volunteer activities.

An idea of the magnitude of a civil defense program that could achieve high shelter occupancy and maintain it for several weeks or longer can be gained from the system envisioned by the 1962 U.S. civil defense guide. The plans, which were never implemented, contemplated that for every shelter accommodating 100 civilians there should be an operating cadre of 25, of whom 10 or 12 would need training. That is, 10 percent of the sheltered population, or 20 percent of the adult population, would have to be trained. To recruit such a large cadre the Government would have to look beyond existing community safety personnel such as policemen, firemen and National Guard units.

One task of these trained people would be to operate communication systems over substantial distances in order to deal with any local shortage of food, water or medical supplies. They would also have to know how to use radiation dosimeters, because in the immediate postattack period the fallout levels could vary greatly from one place to another. (Like snow, radioactive debris accumulates where it is driven, depending on the wind, the weather and the topography, including buildings. There could be pockets of relative safety in the midst of areas with lethal levels of radiation.) The trained cadre would have to provide leadership in the long period of extreme social duress after the attack and reestablish services for a so-



on each of the 10 silos in a flight (*gray circle*) of Minutemen (*2*) and for two warheads on each of the 150 silos in Whiteman's 15 flights (*3 and 4*). The large difference between the bottom two patterns is the result of a change in the assumed wind speed. In all four cases the wind is assumed to blow toward the east. In the first three examples the wind speed is assumed to be constant at 20 miles per hour. In the bottom example the wind speed is assumed to be 60 miles per hour (averaged at altitudes between the surface and the stratosphere).

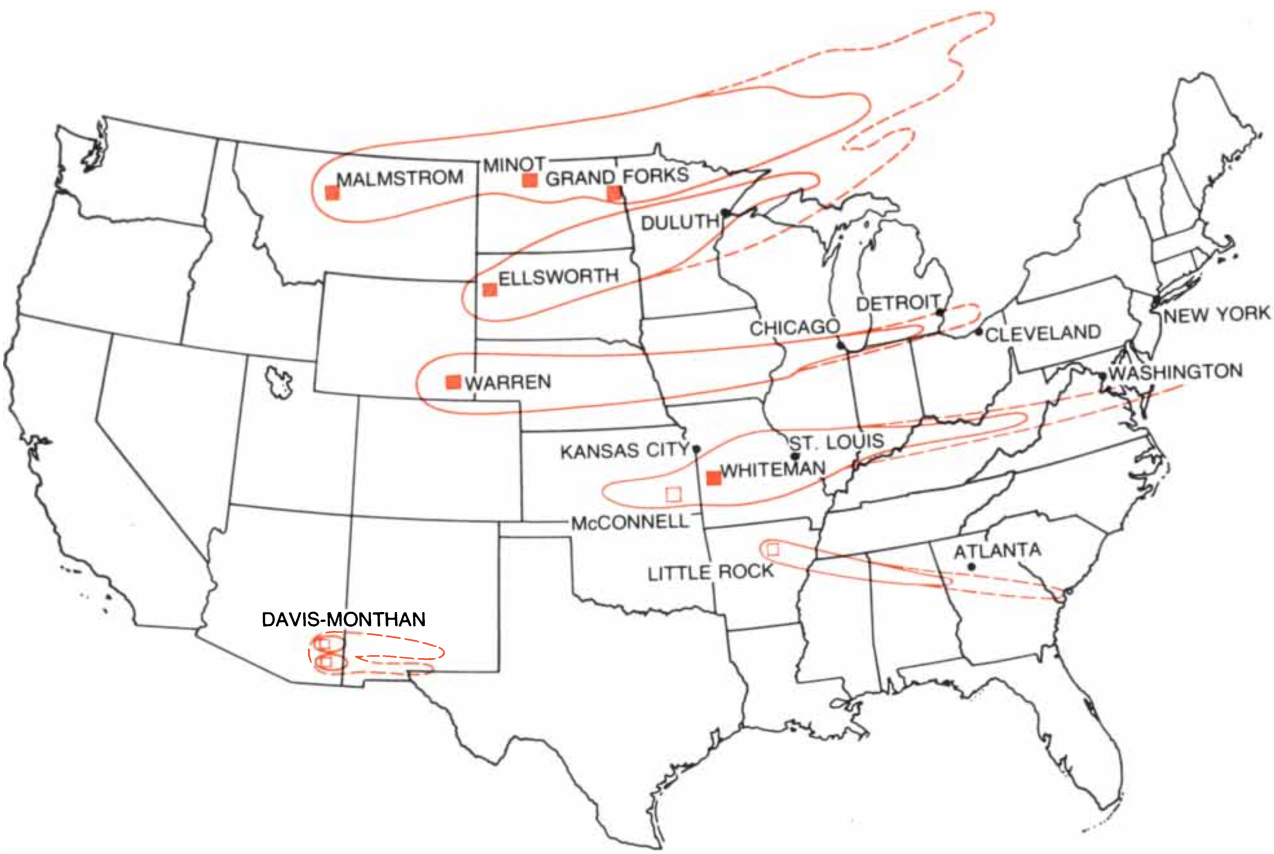
ciety with a large population of sick, injured and dying citizens. It should be noted that Defense Department calculations of the consequences of limited nuclear war are almost certainly serious underestimates. For example, the calculations omit any estimate of what may be one of the gravest consequences of all: the disruption of the intensely interdependent components that enable a modern society to function. The difficulties imposed on a society trying to recover with totally unprecedented levels of mortality and morbidity, with insufficient medical care and with profound dislocations in the supply of food and water are simply ignored. Moreover, the calculations omit any consideration of long-term consequences such as the millions of genetic defects and cases of cancer that would occur worldwide in the decades after the postulated nuclear attack.

A higher level of public awareness and concern and a willingness to participate in repeated civil defense exercises would be required if the U.S. intended to develop a viable system for a massive evacuation and shelter. In the absence of sustained preparation chaos and panic would surely ensue at the time of an attack. It is difficult to see how commitment to such plans could be obtained without a deliberate and sustained intensification of public apprehension concerning a nuclear war. One of the lessons of the relatively ineffective civil defense program of 1961 and 1962 was that the large expenditures for civil defense and the inconveniences of a major shelter program could only be made plausible to the American public by exaggerating the probability of nuclear war.

Today we are again hearing allegations that the U.S.S.R. is developing and rehearsing civil defense plans involving the evacuation and relocation of large populations, along with the dispersal and hardening of industry. These programs are cited to indicate that the U.S. may be losing its deterrent and to spur a renewed U.S. civil defense effort. What evidence is there in support of these allegations?

The Russians have written much on the subject and have given their people more intensive exposure to civil defense than Americans have received. Apparently they have also spent much more money on plans and organizations and have involved in exercises small numbers of individuals with key skills. In view of the unprecedentedly large scale of the nationwide disaster being considered, however, an effective civil defense program would surely have to include among its essential components full-scale rehearsals and survival-living exercises involving the population. If there had been any such rehearsals, we would have heard about them. They would be very difficult to conceal, and many people who would have participated in them or would have had knowledge of them have now left the U.S.S.R. and would have called attention to them. Yet no evidence of such exercises has been presented. The editor of the U.S. Government translation of the official Russian civil defense manual for 1974 comments that "the Soviet Union has not conducted mass shelter living experiments or even simulated ones as has been done in the U.S." Plans and manuals are very different from an effective operating system.

The Defense Department's response of July, 1975, presented new casualty figures and also estimates of the military effectiveness of the postulated attacks. According to the new calculations, a strike with two 550-kiloton warheads, one a surface burst and the other an airburst, against each of the 1,054



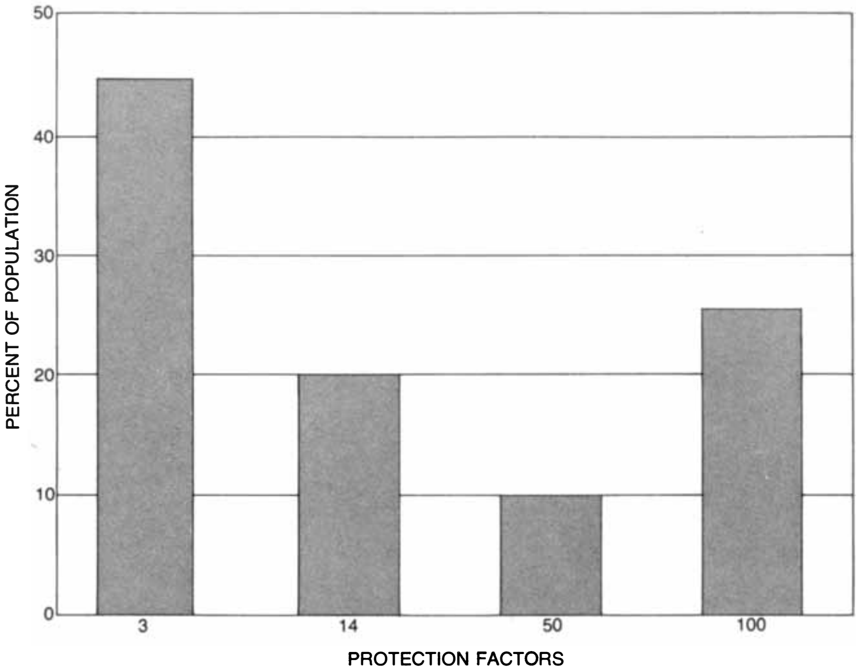
COUNTERFORCE ATTACK on all Titan (*white squares*) and Minuteman (*color squares*) ICBM bases, with two one-megaton surface bursts (50 percent fission yield) per silo, could produce these patterns. Each inner contour delimits a 450-rem dose indoors (50 percent fatalities) and each outer contour a 200-rem dose indoors (50 percent hospitalized). Typical March wind speeds are assumed.

U.S. ICBM silos would cause 5.6 million fatalities (assuming a 25 percent reduction of the population-protection factors given above) and destroy only 42 percent of the silos. A heavier strike with two three-megaton warheads, one a surface burst and the other an airburst, directed at each silo would cause 18.3 million fatalities and destroy 80 percent of the silos. A "comprehensive" attack, with two one-megaton surface bursts on each ICBM silo and strikes against the 46 Strategic Air Command (SAC) bases and the two bases for ballistic-missile submarines, would cause 16.3 million fatalities and destroy 57 percent of the ICBM's, 60 percent of the bombers caught on the ground and 90 percent of the missile submarines in port [*see bottom illustration at right*].

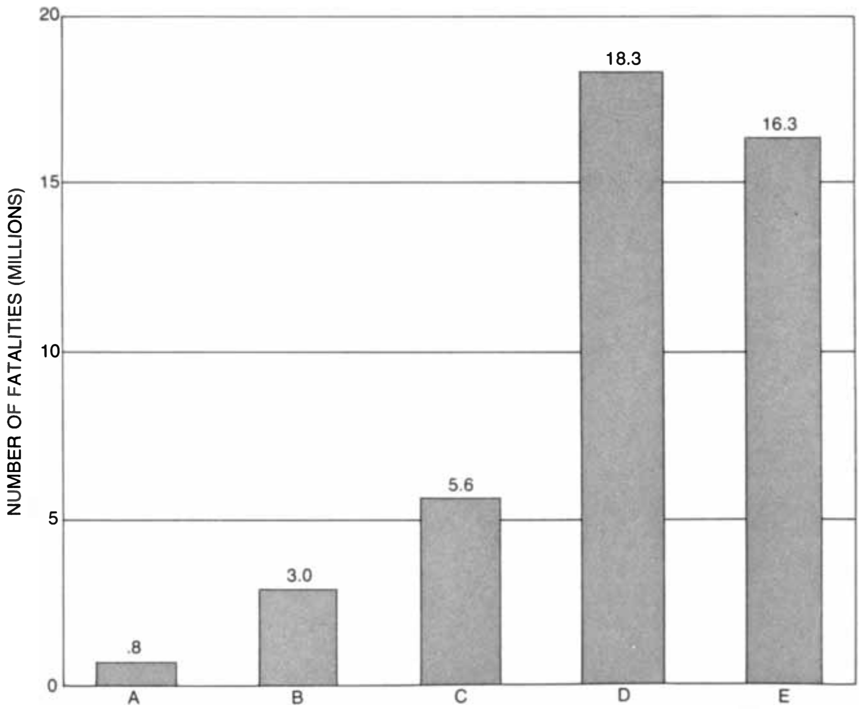
The effectiveness of all these attacks would be somewhat higher if one assumed that the incoming missiles were more accurate and would be somewhat lower if one assumed that the attacking force was less than 100 percent reliable. An additional factor in a massive attack involving many warheads arriving at about the same time in the same area is "fratricide" among the incoming missiles. In a concentrated attack the atmospheric disturbances created by the first warheads to arrive must necessarily destroy, disable or deflect many of the warheads that arrive later. Only the almost perfect synchronization of the arrival of warheads that are aimed at the same silo or nearby silos can avoid this effect.

In any case it is clear that even with a massive attack resulting in enormous devastation, including the direct death of 20 million Americans, the U.S.S.R. would have accomplished little of strategic military value. After the heaviest of the anti-ICBM strikes considered by the Defense Department, more than 200 ICBM's would survive: an overwhelming retaliatory force even if one ignores the SAC bombers, the missile submarines and the thousands of U.S. tactical nuclear weapons deployed overseas and on aircraft carriers. It is therefore at least misleading to suggest that a successful and strategically effective counterforce attack could be carried out with low civilian casualties.

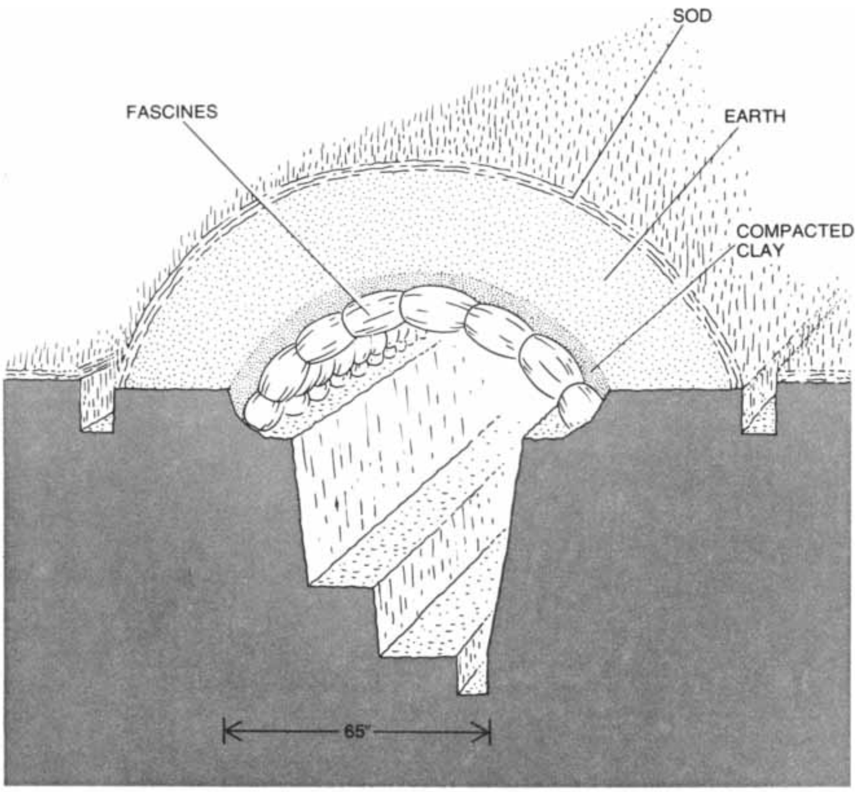
A major danger associated with a policy reorientation that emphasizes preparations for actually waging a limited counterforce war is that it would tend to undermine the stability of the strategic balance. Flexibility is one thing and an efficient hard-target kill capability is another. Flexibility is inherent in the wide range of U.S. strategic weapons, which are targeted on a variety of urban, industrial and military objectives. Any one or any 100 of these weapons could be launched selectively. Furthermore, each missile or bomber has multiple tar-

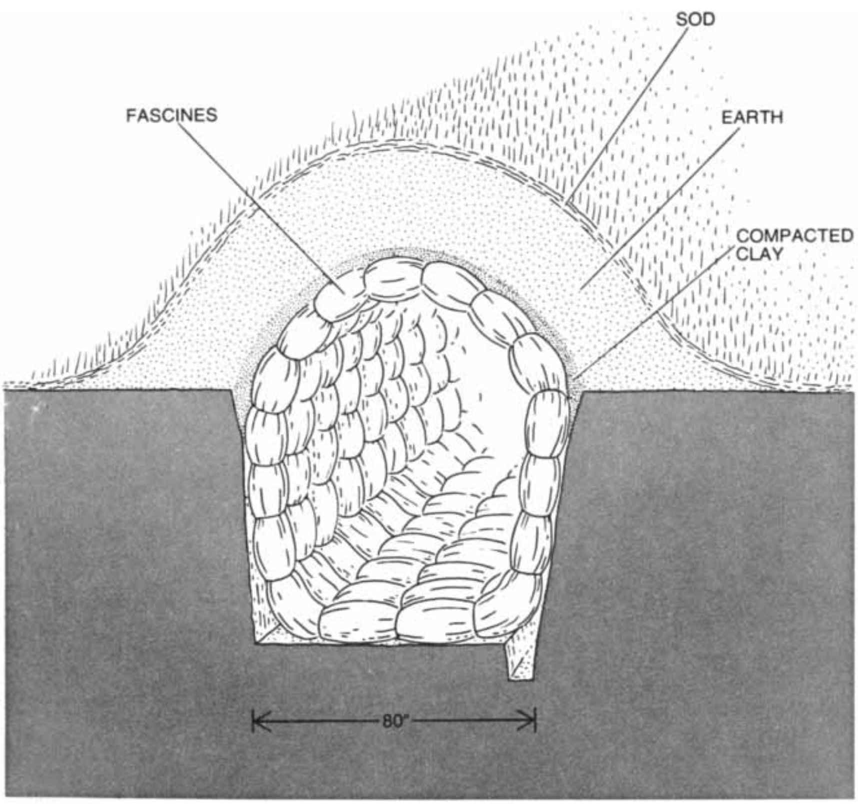


"SHELTER POSTURE" assumed in Department of Defense calculations is given by bars showing what percent of the population is in shelters that have given "protection factors" (the inverse of the proportion of outside gamma radiation penetrating the shelter). A protection factor of 3 is roughly that provided on the ground floor of a one-story residence; the basement of a one-story frame house could provide a factor of 15 to 20, that of a two-story brick house as much as 50. A trench covered by two feet of earth provides a protection factor of about 100.



FATALITIES estimated for five postulated Russian counterforce attacks are shown: one one-megaton airburst on each U.S. ICBM silo (*A*); the same attack with surface bursts (*B*); two 550-kiloton warheads per silo, one airburst and one surface burst (*C*); two three-megaton warheads per silo, one airburst and one surface burst (*D*); a "comprehensive" attack, with two one-megaton surface bursts per silo and with airbursts over all 46 Strategic Air Command bases and the two ballistic-missile submarine bases (*E*). In the last three cases the shelter posture shown in the illustration at the top of the page is "degraded" by 25 percent and March winds are assumed instead of August winds. Also in the last three cases Defense Department evaluated effectiveness of attack: 42 percent of the ICBM's destroyed (*C*); 80 percent destroyed (*D*); 57 percent of the ICBM's destroyed as well as heavy damage to aircraft on ground or flying within eight miles of a base and to submarines in port and base facilities (*E*).





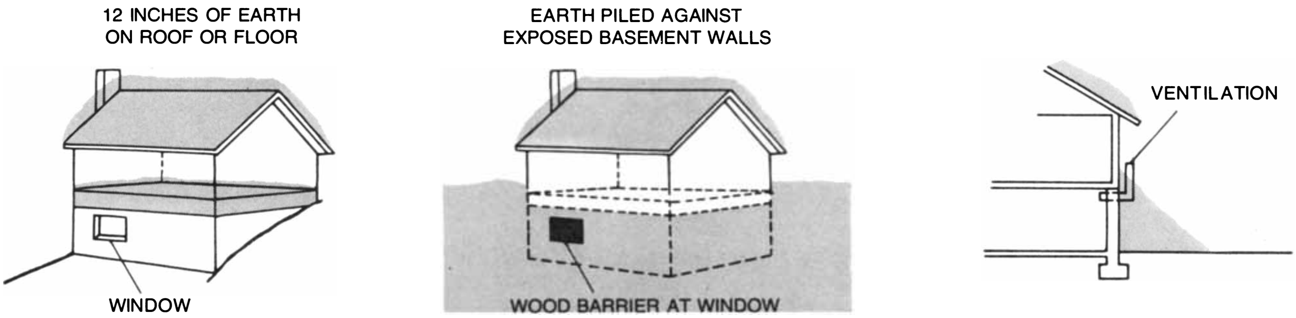
RUSSIAN SHELTER DESIGNS, from a 1970 U.S.S.R. handbook, are for simple structures to be built by people "using available materials and their own labor." A dugout (*top*) in firm clay soil is roofed by rows of fascines (bundles of brushwood, canes or reeds) covered with compacted clay and 30 inches of soil. Rings of fascines are required in looser soil (*bottom*).

get options. The new Command Data Buffer system currently nearing completion makes possible the remote resetting of targets in the on-board computers of Minuteman III missiles from launch-control centers in 36 minutes.

As a result of all this flexibility the U.S. also already has a substantial counterforce capability even without highly accurate warheads. There are, for example, "soft" military targets such as airfields and submarine bases that could be selectively destroyed with a few warheads. Even hard missile silos could be destroyed by hitting each one with a number of Minuteman missiles. The Defense Department nonetheless wants more: the ability to deliver counterforce strikes efficiently and with high confidence against hardened Russian ICBM silos. As Schlesinger put it in his 1976 appropriation request: "I believe we should improve our hard-target kill capability so as to have higher confidence of executing limited hard-target attacks." Indeed, the U.S. is currently progressing toward that goal with funded programs.

These developments clash directly with the need for strategic stability. A U.S. missile force with multiple independently targetable reentry vehicles (MIRV's) or with the maneuverable reentry vehicles (MARV's) now being developed, and with a demonstrated combination of very high reliability, very accurate guidance and high-yield warheads would suggest to Russian leaders the possibility of a U.S. preemptive strike against their ICBM silos. It would further suggest to them that in a time of confrontation they should not be caught with their missiles in their silos, that at such a time they should either strike first or adopt a "hair trigger," or launch-on-warning, policy. The same arguments apply with the U.S. and Russian roles reversed. The current national debate indicates that there is widespread concern, as there should be, about the possibility that the U.S.S.R. might be developing a hard-target counterforce capability, particularly in view of the larger size of the Russian ICBM's.

To be sure, it is impossible to envision a disarming first strike that would really threaten the retaliatory capacity of the U.S.S.R. (or of the U.S.), if only because missile submarines at sea and bombers in the air or on alert are not subject to destruction in a preemptive attack. In order to maintain a stable strategic environment such as the one that now exists for the two superpowers, however, there should be neither a real nor a "perceived" vulnerability of any major component of the strategic deterrent forces on either side. (From the Russian point of view this is true in particular of the land-based ICBM component, since it constitutes a much larger fraction of



U.S. SHELTER DESIGN, redrawn from an illustration published by the Defense Civil Preparedness Agency, is for an "expedient shelter" intended primarily to accommodate evacuated populations. In order to provide adequate fallout protection in a basement that is only partially below ground level it is necessary to put a 12-inch layer of earth overhead and to pile earth against exposed basement walls.

their deterrent power: roughly 75 percent compared with 25 percent for the U.S.) The deployment of missiles with hard-target capability would therefore create tension, because each side would fear that such deployment might lead to the possibility of an effective first-strike threat against its force of silo-based ICBM's. The fact that formidable technical and operational difficulties, such as the fratricide problem, lead many people to challenge the feasibility of achieving such a capability is almost beside the point; there would still be serious concern about the ability of land-based ICBM's to survive a preemptive first strike.

U.S. officials recognize the danger of seeming to threaten Russian retaliatory capacity, and so they couple proposals for an improved hard-target kill capability with announcements that deployment of new offensive weapons would be limited, at least for the time being. But can one acquire just a little hard-target counterforce without bringing on the ill effects of a lot? After all, it is no more than the fear of a possible future Russian ICBM counterforce threat against U.S. Minutemen that has been cited in support of the ongoing programs for improving U.S. missiles. It has been argued that we must be able to respond in kind against each and every perceived potential threat. Schlesinger said that there should be "no perceived asymmetries in levels or capabilities of force—conventional or nuclear."

The danger in this logic is that we will almost inevitably find our own development program triggering a Russian commitment to the very program we fear (and vice versa, of course). All precedents, including in particular the history of MIRV deployment on both sides, indicate that once the technology has been developed and tested for attacking hardened counterforce targets with high confidence, the dynamics of the nuclear arms race will take over and make it difficult if not impossible for the U.S. to refrain from deploying the new weapons extensively and for the U.S.S.R. to refrain from responding in kind.

Neither side has yet developed weapons designed specifically as hard-target killers: weapons that have a high probability of destroying a hardened military target, such as an underground silo, with a single warhead. Research-and-development programs directed toward that goal are, however, funded in this year's U.S. defense budget. Before both countries are committed further and perhaps irrevocably to reciprocally stimulated and mutually reinforcing programs for developing such weapons, the hard questions should therefore be faced up to. Do we really want or need them? What is the value of being able to destroy an enemy silo (which may be empty by the time our warhead arrives) in response to an attack on our own silo? If a small response is wanted, will not an air base or a naval base or a military storage depot do as a target? Is not our current broad flexibility adequate? Will hard-target counterforce weapons make a compelling military contribution to national security or does their justification rest solely on ephemeral politico-strategic argument?

We have argued that such weapons would complicate the problem of maintaining strategic stability. It would therefore seem that it would serve the security of both the U.S. and the U.S.S.R. to avoid their development and deployment. A significant precedent for restraining new weapons in the interest of stability is the treaty, negotiated in the first round of the strategic-arms limitation talks, stringently limiting anti-ballistic-missile defenses. Now again the U.S. and the U.S.S.R. each have a critically important opportunity to limit their traditional technological arms competition by restraining the testing and deployment of new weapons designed to destroy hardened ICBM silos.

In the three decades since Hiroshima and Nagasaki there have been many crises involving the two superpowers, and the U.S. has fought two major land wars in Asia. Yet the armed nuclear truce has persisted. Why has neither side launched a single one of the thousands of nuclear warheads that each has had deployed? Surely it is because of the overwhelming fear of political leaders and citizens on both sides that once a nuclear weapon is detonated there will be an answering detonation, with subsequent exchanges escalating until both nations are destroyed and hundreds of millions of people are dead and dying. The issue created by the new emphasis on a selective, hard-target counterforce strategy accompanied by intensive civil defense efforts is whether or not there is any real prospect of escaping this "balance of terror." Should the assumption that a general nuclear war is prevented by the certainty of mutual destruction be abandoned in favor of the objective of fighting, winning and "surviving" a limited nuclear war when the evidence indicates that even a limited war would cause many millions of fatalities?

In the 1960's the U.S. adopted a strategic policy giving top priority to the prevention of nuclear war through deterrence rather than to preparation for fighting nuclear wars if deterrence should fail. Since then weapons technology has progressed, so that new and more sophisticated kinds of limited counterforce strikes, including attacks on hardened military targets, can be seriously considered. The political reality of deterrence, however, remains unchanged. New technology and new strategy do not significantly reduce the risk of all-out nuclear war breaking out once the first nuclear weapon has been fired.

It is important to recognize that once the nuclear firebreak has been crossed the decision to keep a war limited is no longer in the hands of one side alone; it has to be made by both—or all—participants in the conflict. As Secretary of State Henry A. Kissinger wrote in 1965: "No one knows how governments or people will react to a nuclear explosion under conditions where both sides possess vast arsenals."

Repetitive Processes in Child Development

As an infant grows he acquires certain skills, loses them and then acquires them again. How does this phenomenon fit the concept that behavioral growth is roughly comparable to physical growth?

by T. G. R. Bower

For many years students of child development have conducted their research and formed their theories on the basis of one major assumption: that as a child gets older and progressively bigger he also gets progressively better at any kind of perceptual, intellectual or motor task set for him. That assumption underlies the entire concept of intelligence tests. Such tests are constructed on the notion that the average nine-year-old can do everything the average eight-year-old can do, plus something more, and that the average eight-year-old can do everything the average seven-year-old can do, plus something more, and so forth.

The assumption of progressive development seems to be quite obvious. After all, if one looks at children at various stages in their development, they always get bigger. Although growth is not a continuous or steady process, it never happens that a child who is four feet tall one year shrinks back to a height of three feet six inches the next year. Since such a regression is never seen in physical growth, we would hardly expect to see an analogous regression in behavioral or intellectual growth. Or would we?

Numerous studies, particularly several undertaken in recent years, appear to indicate that behavioral and intellectual development may not be strictly cumulative and incremental. Such studies seem to imply that the pattern of psychological growth may be quite different from the pattern of physical growth. One familiar example is the development of walking. Newborn infants, if they are properly supported, will march along a flat surface, an ability that demonstrates the remarkable sensory-motor coordination of the newborn infant. Yet the ability normally disappears at the age of about eight weeks. Walking of any kind will not usually be seen again until the end of the child's first year.

On a somewhat more complex level, during the first few weeks of life infants can reach out to touch visible objects and will occasionally even grasp them. That eye-hand coordination also disappears at the age of about four weeks and will not be seen again until the age of some 20 weeks. Similarly, young infants have appreciable ear-hand coordination. They are quite willing and able to reach out and grasp objects they can hear but not see, whether they are blind or have normal vision. That ability, which is of obvious practical use to the blind infant in particular, disappears when the infant reaches five or six months, and for the blind infant it may not return at all.

In the area of sensory-motor coordination but at a still higher level of complexity one must include the fact that newborn infants show an extraordinary capacity for imitating the behavior of an adult. For example, they are quite able to imitate an adult sticking out his tongue, opening his mouth or widening his eyes. Indeed, this ability is the most remarkable example known of the competence of the newborn infant's perceptual system. Consider what is involved in imitating someone's sticking out his tongue. The infant must identify the thing he sees in the adult's mouth as being a tongue. (I shall ask the reader to bear with me in my not saying "he or she sees," which makes this kind of discourse unduly cumbersome.) He must realize that the thing he cannot see but can feel in his own mouth is also a tongue, the homologue of the thing he sees. He must then execute fairly complex muscular movements in order to imitate what he sees. The activity of imitation seems to be basically a social ability. The infant and his mother become raptly involved with each other as they play games of imitation. In spite of the fact that the ability manifests itself so early in life it soon seems to fade away, reappearing only toward the end of the child's first year.

The apparent loss of abilities is not limited to sensory-motor skills. It is also not limited to the period of infancy. The pattern of loss and reacquisition of capacities extends to abstract intellectual abilities and persists all the way through childhood. For example, adults know perfectly well that the weight of a lump of modeling clay does not change with changes in its shape. This is a fact a child must discover not once but three times in the course of his development.

If a one-year-old child is presented with a ball of modeling clay, he will probably misjudge its weight the first time he picks it up. After he has been presented with the ball two or three times, however, his behavior will clearly show that he knows the weight of the object. He can pick it up without his arm wavering and put it unerringly wherever he wants. Suppose that the ball of clay is then rolled into the shape of a sausage with the child watching. What happens when he picks up the sausage? Typically his arm will fly up over his head, indicating that he thinks the object has become much heavier because it has become longer. He makes the opposite kind of mistake if the experimenter begins with a sausage-shaped piece of clay and then molds it into a ball. In short, a one-year-old child has not mastered the concept of the conservation of weight.

If one gives the same child the same task at 18 months, he makes no mistakes at all. If his behavior is taken to be an index of what he knows, one can say that the 18-month-old child knows that the weight of an object does not change when the shape of the object is changed. In short, an 18-month-old child does apprehend the concept of the conservation of weight.

If the same child is asked two years later what happens to the weight of a ball of clay when it is rolled into the shape of a sausage, he will probably answer that the sausage is heavier than the ball because it is longer. Furthermore, if the child is then presented with the identical behavioral test he was given as an infant, he will once again make the mistakes he made at the age of a year—mistakes he did not make at 18 months. Again if the child's behavior is taken as an index of what he knows, it seems as though he has once more lost the concept of the conservation of weight.

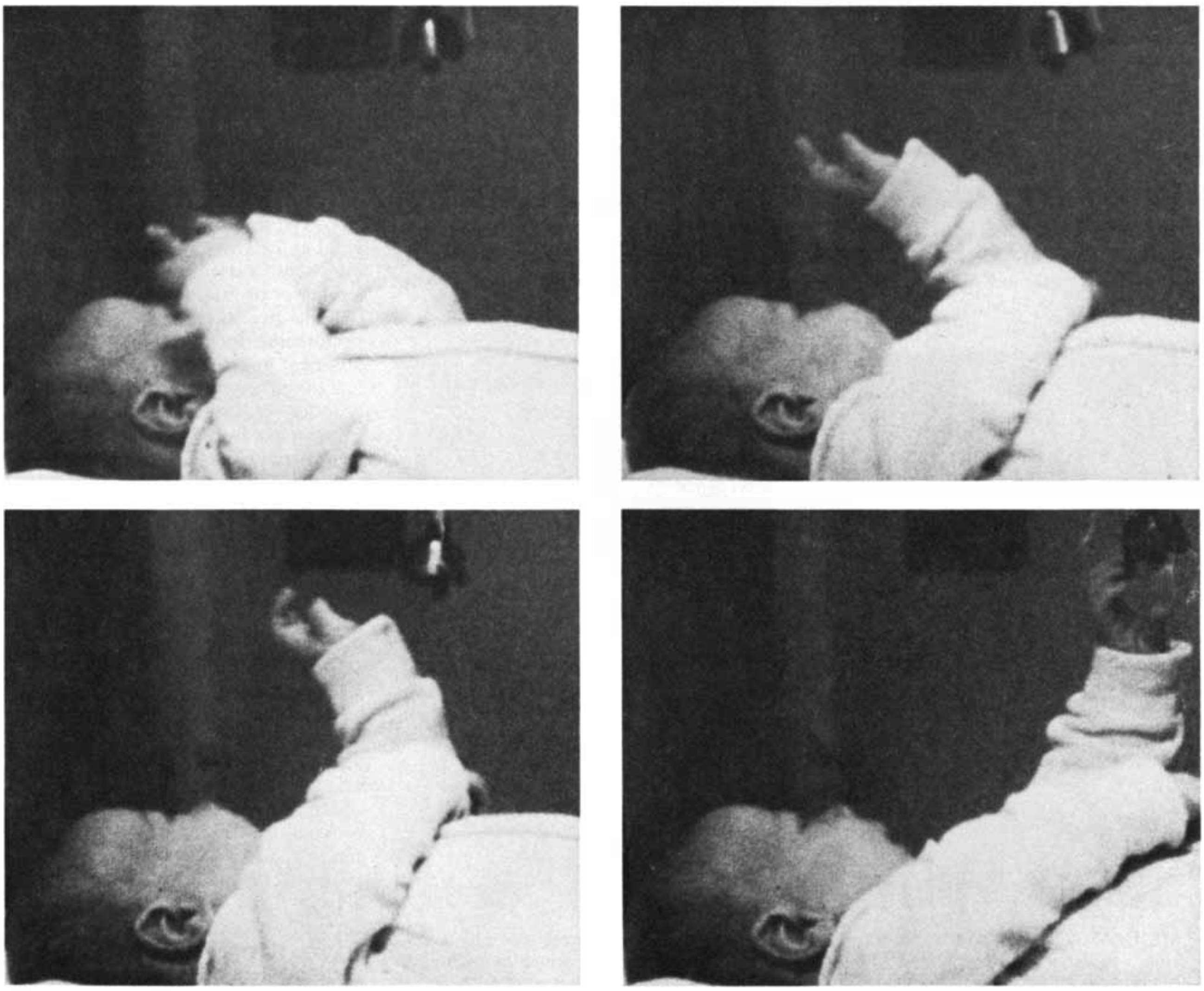
Normally the child reacquires the concept of the conservation of weight, exhibited both behaviorally and verbally, at the age of seven or eight. The acquisition of the concept, however, is not complete at that stage. If the child is given the same test at 11 or 12, he will again give the wrong verbal response, just as he did at the age of four. It is not known whether his performance in the behavioral test will decline as well, because no one has yet tested it. It seems likely, however, that it would decline, because behavior usually follows language. Not until age 13 or 14 does the child arrive at a stable concept of the conservation of weight.

Observations such as those I am describing seem to be at odds with the view that psychological growth is a continuous incremental process like physical growth. Abilities seem to appear and then disappear, leaving the child worse off than he was when he was younger, perhaps even no better off than he was as an infant.

There is evidence, however, that the various phases of development are connected. It has been shown, for example, that if an infant practices walking at the very early phase, the experience will accelerate the appearance of walking later. It has been suggested that the acquisition of certain concepts in infancy is necessary for the permanent emergence of those concepts later in life, and that a child who does not acquire normal concepts during infancy may be permanently unable to acquire them. There are data that appear to support this suggestion. It would therefore seem that the study of repetitive processes in development has a practical value. The observations, however, complicate the theoretical puzzle. How can something that disappears be critical for subsequent development?

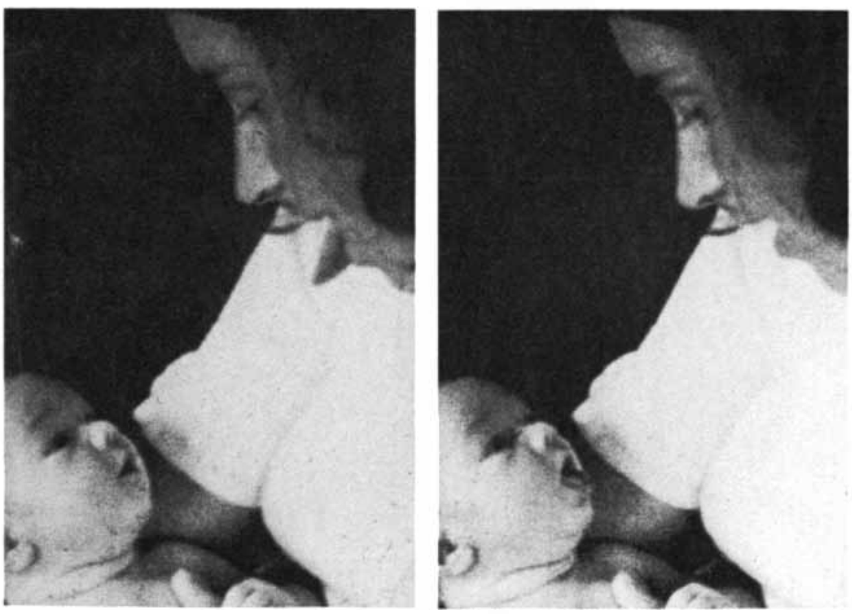
I personally have been fascinated by repetitive processes in development for many years. When I began studying them, I made the naïve assumption that a repetition is a repetition, and that studying any specific type of repetition, either sensory-motor or cognitive, would ultimately yield a general theory of repetition in development. Therefore I concentrated on the simplest and quickest of the repetitive processes: reaching.

There are two obvious questions involved in studying any repetitive process. First, why does the earliest phase of gaining an ability—let us call it Phase 1—come to an end? Second, what is the relation between Phase 1 and Phase 2 or



NEWBORN MALE INFANT REACHES out and touches a bell with no hesitation at the age of 10 days, demonstrating the remarkable organization of the newborn perceptual system and a high degree of eye-hand coordination. Yet when the infant attains the age of four weeks, the ability will disappear, and it does not reappear for another four months. These photographs, which read from left to right and top to bottom, are frames from a motion picture of the infant made in the author's laboratory at the University of Edinburgh.

SIX-DAY-OLD FEMALE INFANT WALKS much like an older child if she is properly supported on a flat surface. This remarkable sensory-motor ability disappears at the age of about eight weeks and does not reappear in any form until the end of the child's first year.



SIX-DAY-OLD FEMALE INFANT IMITATES her mother's protruding her tongue. The ability to imitate is a much more complex achievement than either reaching or walking: it requires the infant to recognize that what she sees in her mother's mouth is a tongue (*left*) and that what she feels in her own mouth but cannot see is also a tongue. Then the infant must execute complex muscular actions required for her to protrude her own tongue (*right*). The ability to imitate also seems to disappear early, reappearing only near the age of one year.

any succeeding phase? On the basis of the methods of study available it is in fact difficult to establish that there is any relation between two phases of behavior that are separated in the full span of development. About the only paradigm that is of any value is the hypothesis of early practice; if one can show that practicing one type of behavior in Phase 1 affects the emergence of Phase 2 of that behavior, then one has made a case in favor of the hypothesis that the two phases are connected. It is not a watertight case, to be sure, but it is a case.

Accordingly I gave several groups of infants intensive practice in reaching during Phase 1, the first four weeks of life. The results were moderately clear and were in accord with what earlier investigators had concluded from studies of walking: the more the behavior was practiced in Phase 1, the earlier it appeared in Phase 2. In my own studies there were even cases where reaching ability was not lost after Phase 1.

Such results pointed to the possibility that the reason abilities disappear is that they are not exercised. Given practice and reinforcement, I hypothesized, the abilities might not disappear at all. If they did not, that would confirm the traditional theory that psychological development is a continuous and incremental process like physical growth.

To test this hypothesis my colleagues and I at the University of Edinburgh administered a selection of various tasks to a number of infants only days or weeks old and gave them intensive practice in performing the tasks as soon as their abilities appeared. The results were mixed, to say the least. For example, practice of ear-hand coordination in Phase 1 actually accelerated the disappearance of the coordination and retarded its reappearance in Phase 2. This seemed to be true both for normal infants tested in darkness and for one blind infant. On more cognitive tasks the results were inconsistent. Sometimes practice during the early phase of an ability accelerated the reappearance of that ability, but increasing the amount of practice did not increase the rate of acceleration.

As an example, one task we gave the infants was a counting problem that involved a form of conservation. A child was shown candies in pairs of rows in which the length of the rows, the spacing between the candies and the number of candies varied. The child was then allowed to choose the row he wanted. If he always chose the row with more candies, it was concluded that he had a primitive ability to count. A high proportion of children between the ages of two and two and a half can give correct verbal responses to the problem. Thereafter they are unable to respond correctly until they are nearly five. Even before the age of two there is a phase in which children can respond correctly to such tasks (although at that age they cannot respond verbally). It was this initial phase that we investigated. With practice the children's choice responses became quite exact. Yet at the usual age of two or two and a half, when other children can give correct verbal responses, only a small proportion of the children with practice responded correctly. The proportion of the children who finally did acquire the ability to give correct verbal responses by age five, however, did not seem to be affected.

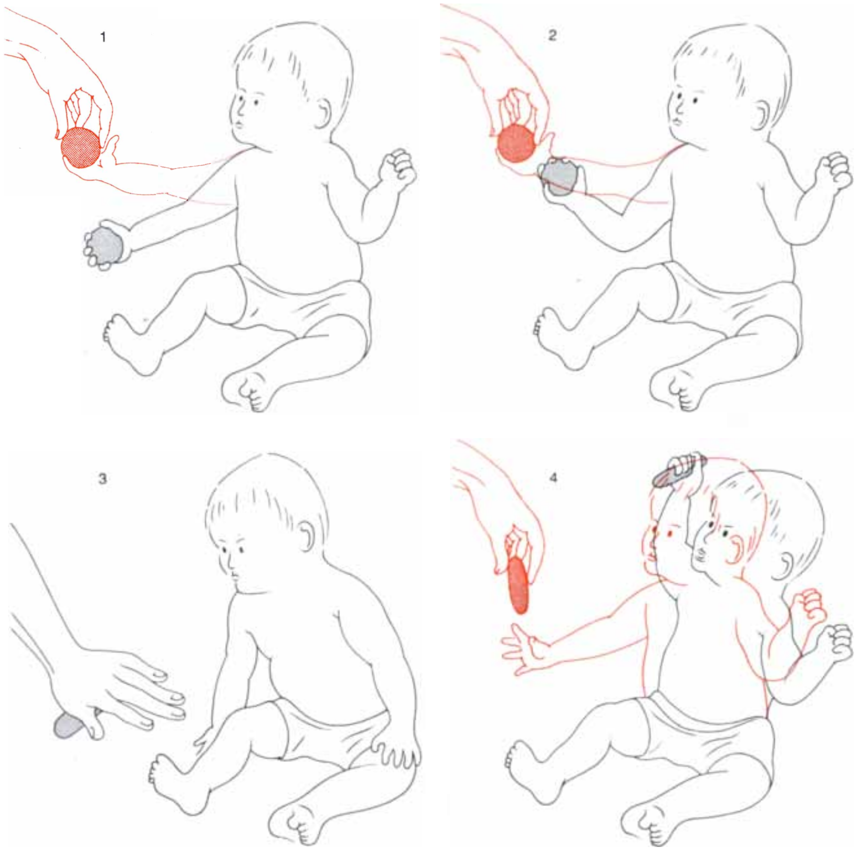
Disappointed that our first explanation of repetitive processes in development had failed, we decided to return to our previous study of reaching and to reexamine the characteristics of reaching in Phase 1 with respect to the characteristics of reaching in Phase 2. We had found that the infants who had practiced reaching in Phase 1 were better at reaching when the ability reappeared in Phase 2 than infants who had not been given any practice in Phase 1. Specifically, they were more skilled than untrained infants at seizing dangling objects presented in a variety of positions. They were particularly good at reaching under conditions of visual distraction.

In one study we fitted the infants with specially constructed glasses consisting of two thin wedge prisms instead of lenses. The prisms displace the apparent location of an object with respect to its real location. Normal infants who had had no practice in reaching would reach toward the apparent location of the object, thereby missing it. Then they would lie still for a time, with both the object and their hand in their visual field, before pulling their hand back, reaching again and missing again. These infants seemed quite incapable of using the sight of their hand to correct their behavior in reaching.

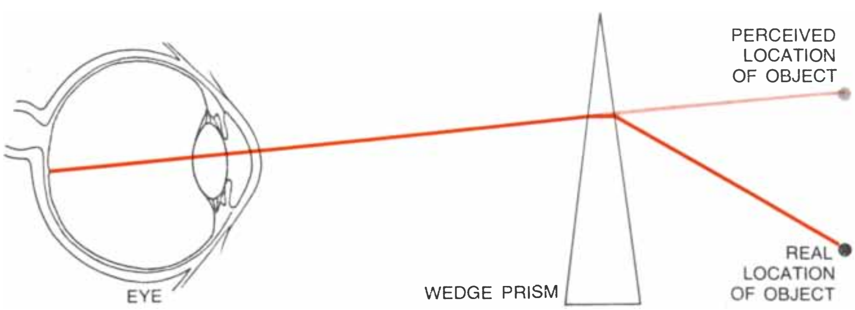
In contrast, older infants who had had no practice in reaching and somewhat younger ones who had been given early practice would first reach toward the incorrect location and then as soon as their hand came into view would correct its motion and home in on the object with perfect accuracy. They were thus able to use the visible position of their hand to correct its motion. Normal infants who have had no practice acquire this ability at an average age of 24 weeks, whereas the infants who had been given early practice succeeded at the task at an average age of 19 weeks.

This accelerated flexibility was acquired at a price, as a second experiment soon showed. For the experiment the infants were put in an illuminated but light-tight room. They were shown a toy but were kept from reaching for it until after the room lights had been switched off. They therefore had to reach for it in the dark. Their behavior in the dark was monitored with an infrared television camera. The younger infants, as one might expect from our wedge-prism experiment, were not distracted by the darkness: their hands went straight out to grasp the object. The older infants and the accelerated ones were quite uncertain. Although they too reached out, their reaching was not at all direct; they fumbled for the object instead of grasping it. It seemed that their ability to employ visual guidance had brought them to rely on it, so that without visual guidance they were lost.

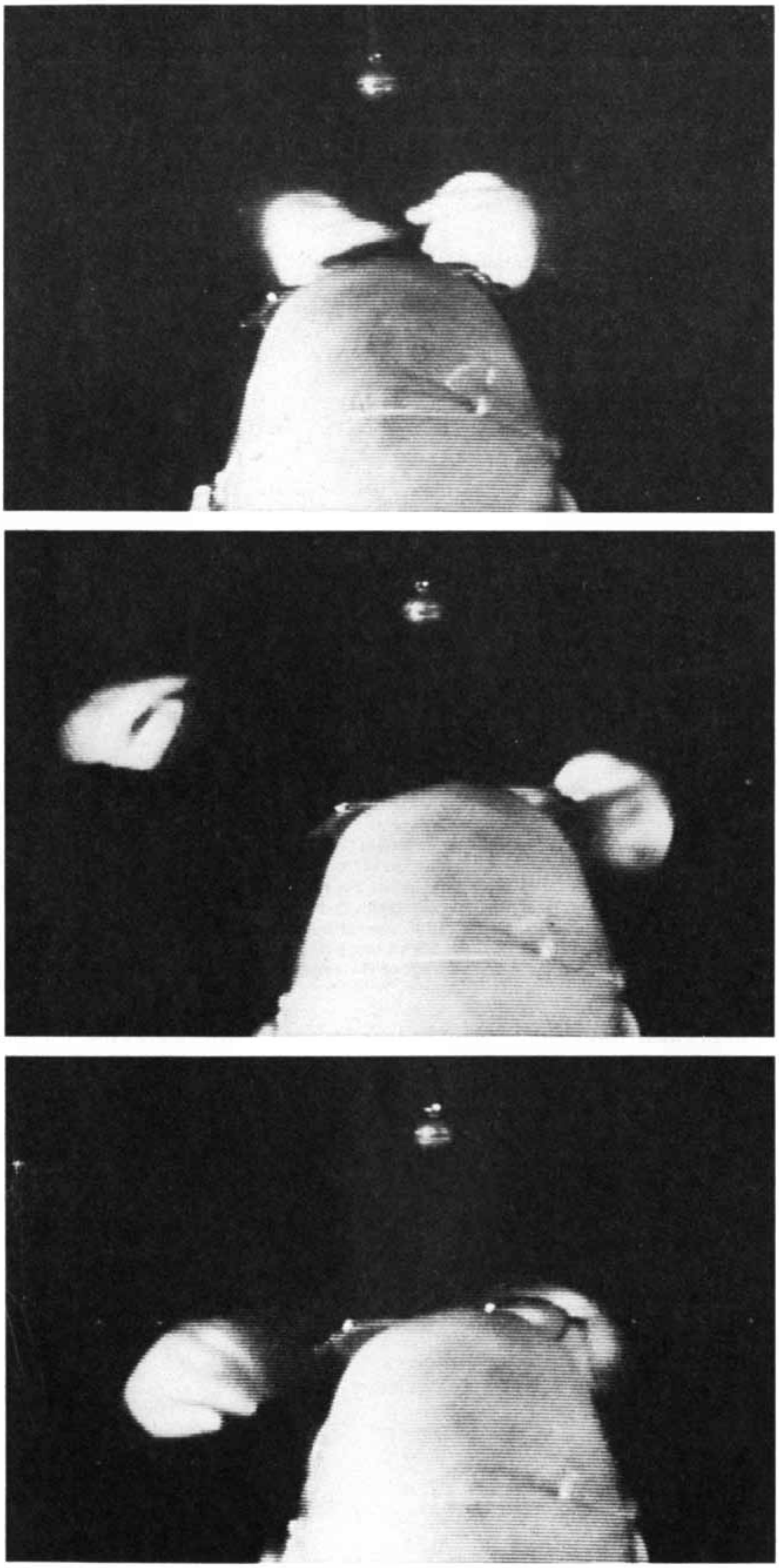
If the main change in the development of a child's ability to reach is the acquisition of visual control, how did



CONCEPT OF THE CONSERVATION OF WEIGHT may be acquired not just once but three times in the course of a child's development. If a one-year-old child is handed a ball of modeling clay, he will typically misjudge its weight the first time it is presented to him (*1*). Soon, however, his behavior indicates that he has learned to estimate the weight of the object before he holds it (*2*). The ball of clay is then rolled into the shape of a sausage with the child watching (*3*). When the child holds the sausage, typically his arm flies up (*4*), indicating that he thinks the sausage is heavier than the ball because it is longer. This erroneous behavior disappears by the age of about 18 months, only to reappear and disappear twice more much later. A child finally acquires a stable concept of the conservation of weight early in his teens.



WEDGE PRISM fitted to glasses displaces the apparent location of an object from its actual location. The effect of wedge prisms on infants can be seen in illustrations on next two pages.



YOUNG INFANT WEARING WEDGE PRISMS reaches toward the place where he perceives an object to be and misses. After resting for a while with both his hand and the object in his field of view, he reaches and misses again. He seems unable to use his vision to correct the position of his hand. Horizontal lines across photograph are scan lines of television camera.

practice during Phase 1 of reaching accelerate the appearance of visual control in Phase 2? It is clear that reaching for an object with visual guidance calls for more attention than reaching without such guidance: for the infant to attend to both his hand and the object will take up more of his attentional space than if he simply attends to the object. It is also clear that infants cannot initially attend to both their hand and an object. At some age the hand and the object actually seem to compete for attention. The early practice would therefore result in the hand's being in the visual field much more often than it was without such practice. For the accelerated infants the hand would thus be a more familiar sight. It is known from many other studies that familiar objects require less attentional space than unfamiliar ones. Hence it is possible that practice during Phase 1 of reaching accelerated the appearance of Phase 2 of reaching by making the infants more familiar with the sight of their own hand.

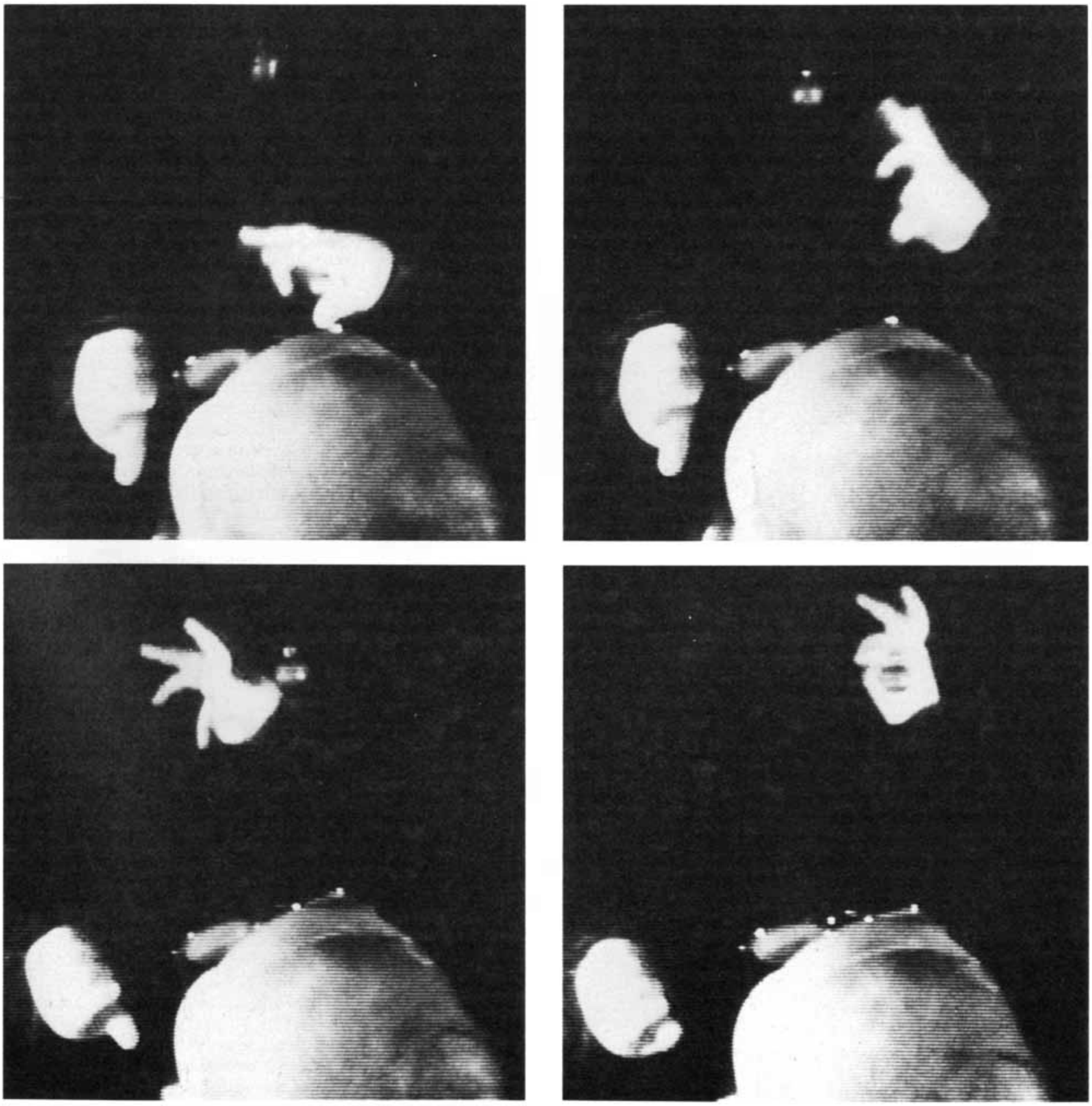
Even if this explanation for the development of reaching is correct, there is no reason to expect that the same explanation will apply to the repetitive appearance of abilities other than reaching. It seemed necessary to look for additional explanations for the other repetitions, thereby forsaking the hope of constructing a general theory of repetition in development. Indeed, different specific explanations for different specific abilities were readily forthcoming. For example, the remarkable ability of newborn infants to imitate adults disappears at a certain age. Colwyn Trevarthen of Edinburgh has pointed out, however, that infants in the age group that will not imitate adults are nonetheless delighted if they themselves are imitated. If an infant is to recognize that he is being imitated, he must have at his disposal exactly the same perceptual tools he would need in order to be able to imitate someone else. The decline in an infant's imitative behavior hence may not imply any loss of ability but rather may indicate a change in motivation. The infant still has the ability to imitate, but he chooses to employ it to detect others' imitation of him.

Including changes in motivation in the list of possible hypotheses for seeming repetitions in development led us to what I believe is the correct explanation for the sometimes permanent decline in ear-hand coordination. The explanation stems from the difference between the normal conditions of visual stimulation and those of auditory stimulation. The situation of the infant with respect to visual stimulation is normally an active one: he can look at things that interest him and he can look away from things that bore or disturb him. He can close his eyes if he wants to. His situation with respect to auditory stimulation is quite different: it is a passive one. The infant cannot switch on sounds he likes or switch off sounds he dislikes. There is no way for him to shut his ears as he can shut his eyes. In short, he has no control over auditory input.

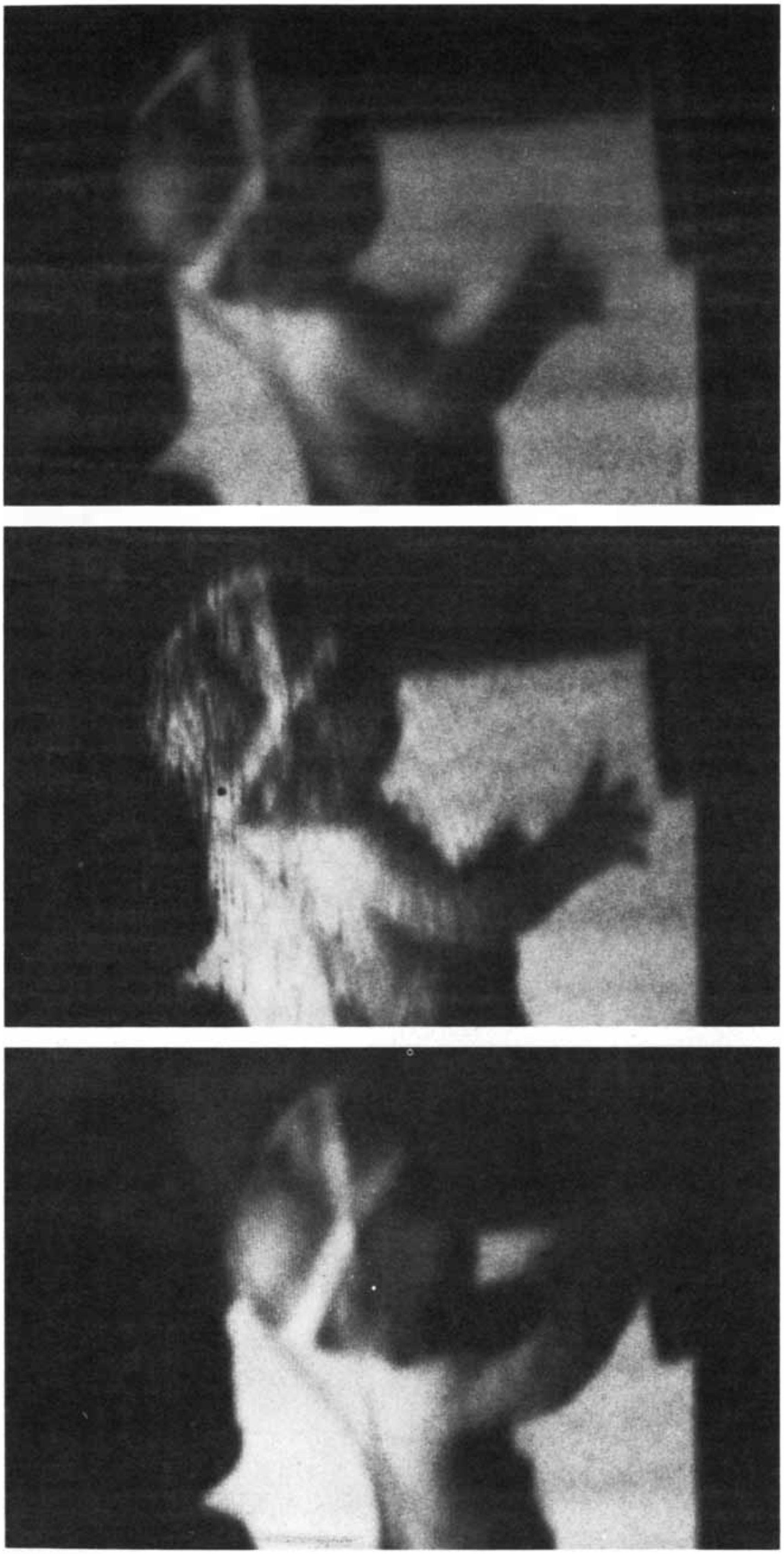
Passive situations of this type have important effects on development. The classic experiments on the effects of passivity were done with vision, using kittens as the subjects [see "Plasticity in Sensory-Motor Systems," by Richard Held; SCIENTIFIC AMERICAN, November, 1965]. Kittens that were raised for as short a period as 30 hours in conditions where they were not allowed to respond actively to visual stimulation became functionally blind. When they were presented with any type of visual stimulation, they showed no response.

The results of the kitten experiments suggested to us that the reason human infants lose their auditory-manual coordination is that they are passive in the presence of auditory stimulation. How could we present auditory information to the infant in such a way as to give him an active role?

After some trial and error we found that the answer was to fit the infant with an ultrasonic echo-location device. The device sent out pulses of sound waves at ultrasonic frequencies in a cone with a width of 80 degrees. Since the frequency of the sound was so high, the pulses could not be heard. Ultrasonic echoes bounced off any object in the field of the device. The device itself converted the ultrasonic echoes into audible sounds that were channeled directly into the ears of the infant. The closer the object was to him, the lower the pitch of the sound he heard was, and the larger the object was, the louder the sound was. Objects to the right of the infant produced a louder sound in his right ear, and objects to the left produced a louder sound in his left ear. Objects that were straight ahead produced sounds that were equally loud in both ears. Hard



OLDER INFANT WEARING WEDGE PRISMS reaches toward the apparent location of an object and also starts to miss the object. **As soon as his hand enters his field of view, however, he uses his vision to correct its trajectory and to accurately home in on the object.**



BLIND INFANT WEARING SONAR DEVICE has active control over his auditory inputs, much as a normal infant can control his visual inputs by closing his eyes or looking away. The device sends out ultrasonic waves that are reflected from objects. The echoes are then converted by the device itself into audible tones. The nature of the tones depends on the distance, size and texture of the objects. In this sequence of photographs when the blind infant is moved by an adult toward a metal pole, he puts out his hands as he gets close, as a normal child would.

objects made a clear sound and soft objects made a somewhat fuzzier one.

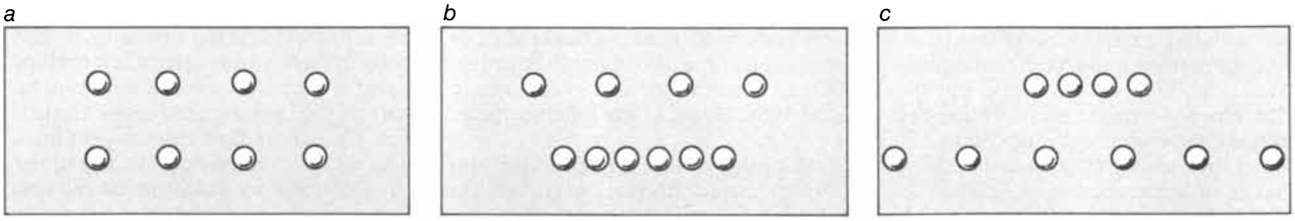
The most important characteristic of the device, however, is that anyone wearing it has direct control over the sounds it channels to his ears. The wearer can focus on interesting objects; he can turn away from boring objects and thereby silence them; he can inspect objects by moving past them, and so on. In other words, the wearer has active control over at least this type of auditory stimulation. If our hypothesis about the disappearance of normal auditory-manual coordination is correct, behavior guided by the ultrasonic device should not disappear.

The device has been tested only on one infant who is congenitally blind. The results, however, were quite satisfactory. Not only did auditory-manual behavior not decline but also the infant actually developed some skills comparable to those acquired by a normal infant of the same age. Furthermore, the experiment clearly showed the flexibility of the newborn infant's perceptual system. No organism in the history of life had ever received the inputs this infant was given, yet he began making sense of the sounds within seconds after the device had been put on.

Of the major types of repetitive processes I have described, the only type for which I have offered no explanation is the cognitive repetitions. We do, in fact, have an explanation for them, but it is extremely complex. Some of the experiments we have devised to test the explanation, however, have shed a most intriguing light on the nature of intellectual development, particularly that in infancy.

Our explanation for the repetitions in cognitive development is based on data from experiments on short-term perceptual development. Consider a simple experiment on habituation. If one shows an infant a cube in a constant orientation 10 times for a period of 30 seconds each time, he will look at the cube progressively less and less. This decreasing level of attention indicates that the infant has recognized that he is seeing the same object each time. Suppose one now shows the infant a cube 10 times but each time the cube is in a different orientation. The result is that the infant shows exactly the same decline in the amount of time he spends looking at the cube.

This phenomenon yields a great deal of information about how an infant remembers objects. Clearly the infant cannot have in his memory a very specific image of the cube in a specific orientation, because every time the cube is presented the orientation is different. This means that the infant must remember from one presentation to the next what shape a cube is without remembering the orientation of the cube. This kind of



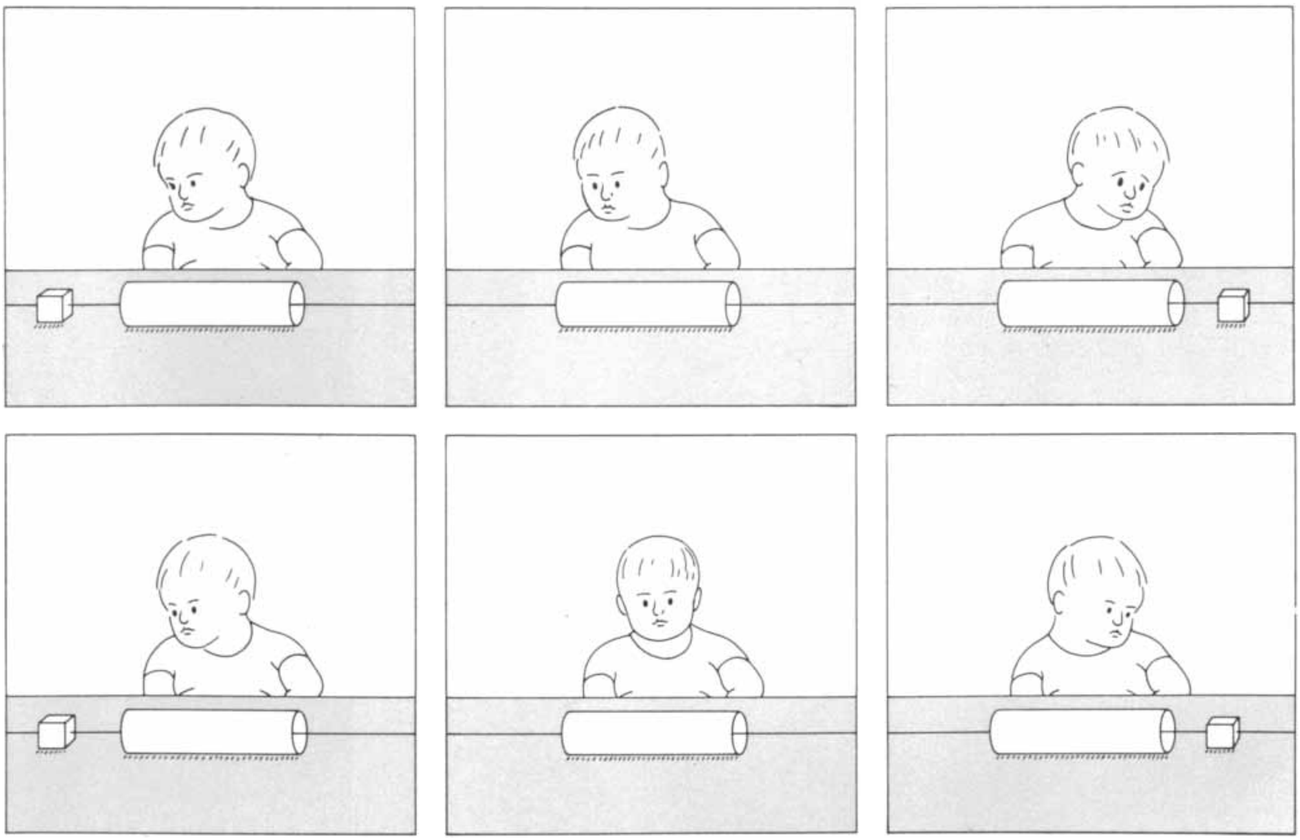
COUNTING TASK, administered to children old enough to talk, involves the concept of number. The experimenter first shows the child two equally long rows of candy (*a*) and makes sure that the child agrees there are the same number of pieces of candy in each row. Then the child is shown a different pair of rows (*b or c*) and is allowed to pick whichever row he wants. The object is to see whether or not he will choose the row with more candies in it without regard to how long the row is and how close together the candies are. If child always chooses row with more candies in it regardless of arrangement of pieces, one can assume that he has a primitive ability to count.

memory is actually rather abstract; indeed, it must be almost as abstract as a word is. It also lacks the details of the object, even details as important as orientation. Nevertheless, if the infant is given enough time, he can internally work up a quite detailed description of the object, so that even a very slight change in it will arrest the decline in his looking behavior. Thus the infant's internal description of an object can change from being rather abstract to being quite specific.

My colleagues and I propose that there is a similar kind of process underlying cognitive development: as the child grows older he progressively elaborates his internal descriptions of events to make them more specific. Such a change in favor of more specific description acts to decrease the likelihood of a smooth transfer from one skill to another, thereby increasing the likelihood of a seeming repetition. Consider the problem presented to an infant by the sight of an object entering one end of a tunnel and emerging from the other end. Initially the infant may refuse to look at this kind of display. Once he has recognized that the object he sees at either end of the tunnel is the same object, which is no easy feat, he must then figure out what is happening to the object when it is out of his sight [see "The Object in the World of the Infant," by T. G. R. Bower; SCIENTIFIC AMERICAN, October, 1971].

I propose that the infant's first discovery is that one object can go inside another and still exist. That is a relatively abstract hypothesis about the world; it will not particularly improve the infant's skill at tracking the object through the tunnel. What the hypothesis will do is allow the infant to shift his understanding from the tracking situation to other situations. Suppose an infant who understands this hypothesis now sees a toy placed under one of two cups. He should now know that the toy is under a specific cup and therefore be able to retrieve it. If the toy is placed under the other cup, he should be able to retrieve it from under that cup. That is exactly what happens if the infant is given this transfer task.

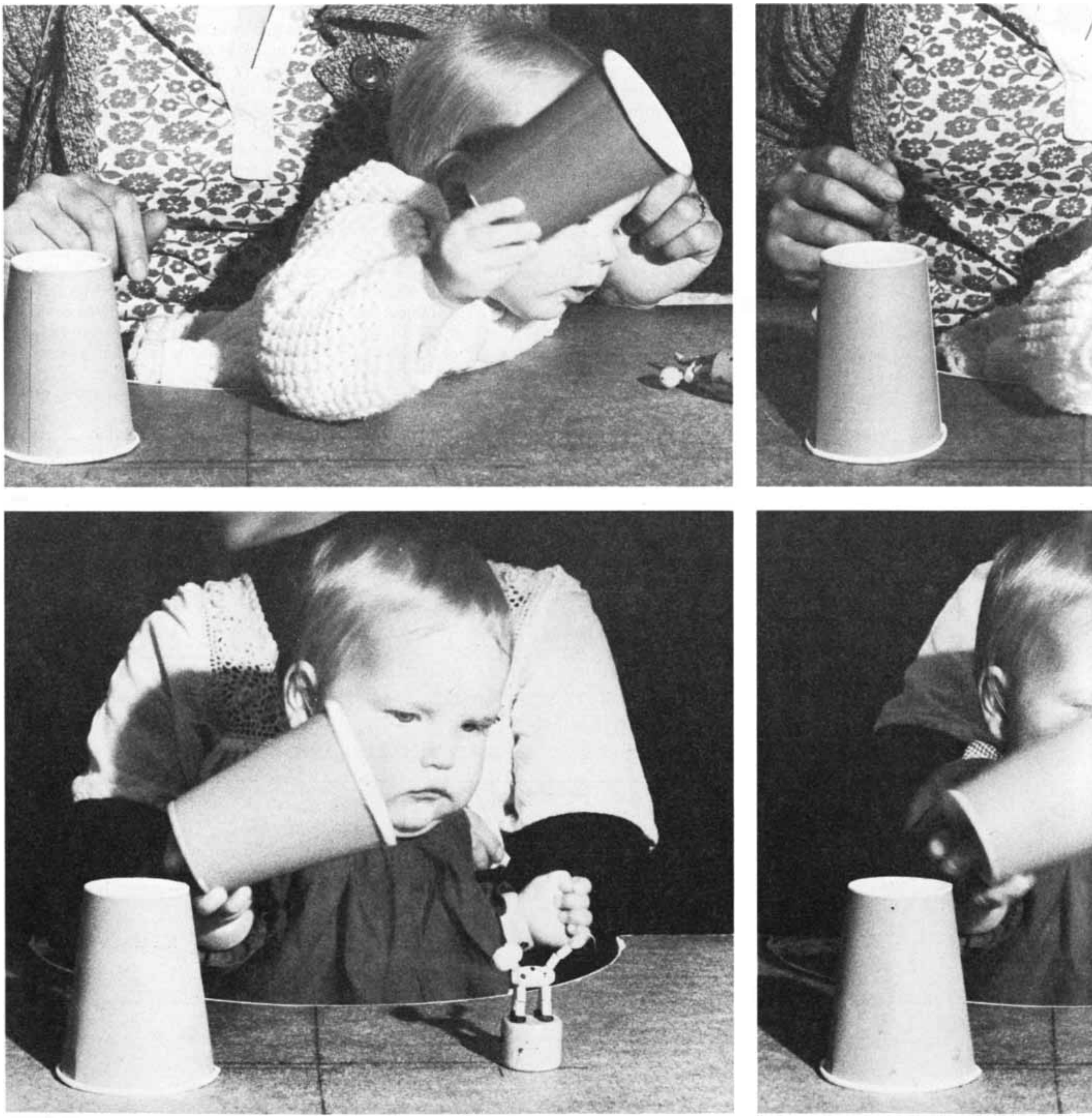
If the infant is then given more prac-



TRACKING TASK presents an infant with an object going into one end of a tunnel and then after several seconds reappearing at the other end. At first infants may be surprised and disturbed by this kind of display (*three panels at top*). They may even refuse to look at it until they learn that one object can go inside another and still exist. After they acquire the concept they can with practice track the object so accurately that they can move their eyes unerringly to intercept the object at any point in space (*three panels at bottom*).

tice with the tunnel-tracking task, however, something quite different happens. After a while he readily works out specific sensory-motor rules enabling him to track the object quite efficiently. He shows by his behavior that he knows that in order to see the object that has vanished at the left end of the tunnel he must look for it at the right end of the tunnel after *x* seconds. His knowledge of the spatial and temporal nature of the tracking task becomes very detailed indeed. Infants who have had weeks of experience with tracking tasks do not spend much time looking at the display, but they can move their eyes unerringly to catch the object at any point in space.

If such infants are again given the toy-under-the-cup transfer task, they do better than infants with no experience in the tracking task. They do not do as well, however, as other infants who are given the transfer task after having had some tracking experience but not as much as they had had. In particular, if the infant watches the toy being placed under the second cup after a few trials of seeing it placed under the first cup, he will still tend to look for it under the first cup. Thus the infant seems to repeat a phase in his development, failing to understand for a second time the relation between two objects when one is inside the other. What causes such a repetition, I suggest, is that with so much practice at tracking an object going through the tunnel the infant has evolved such specific rules in dealing with the tracking

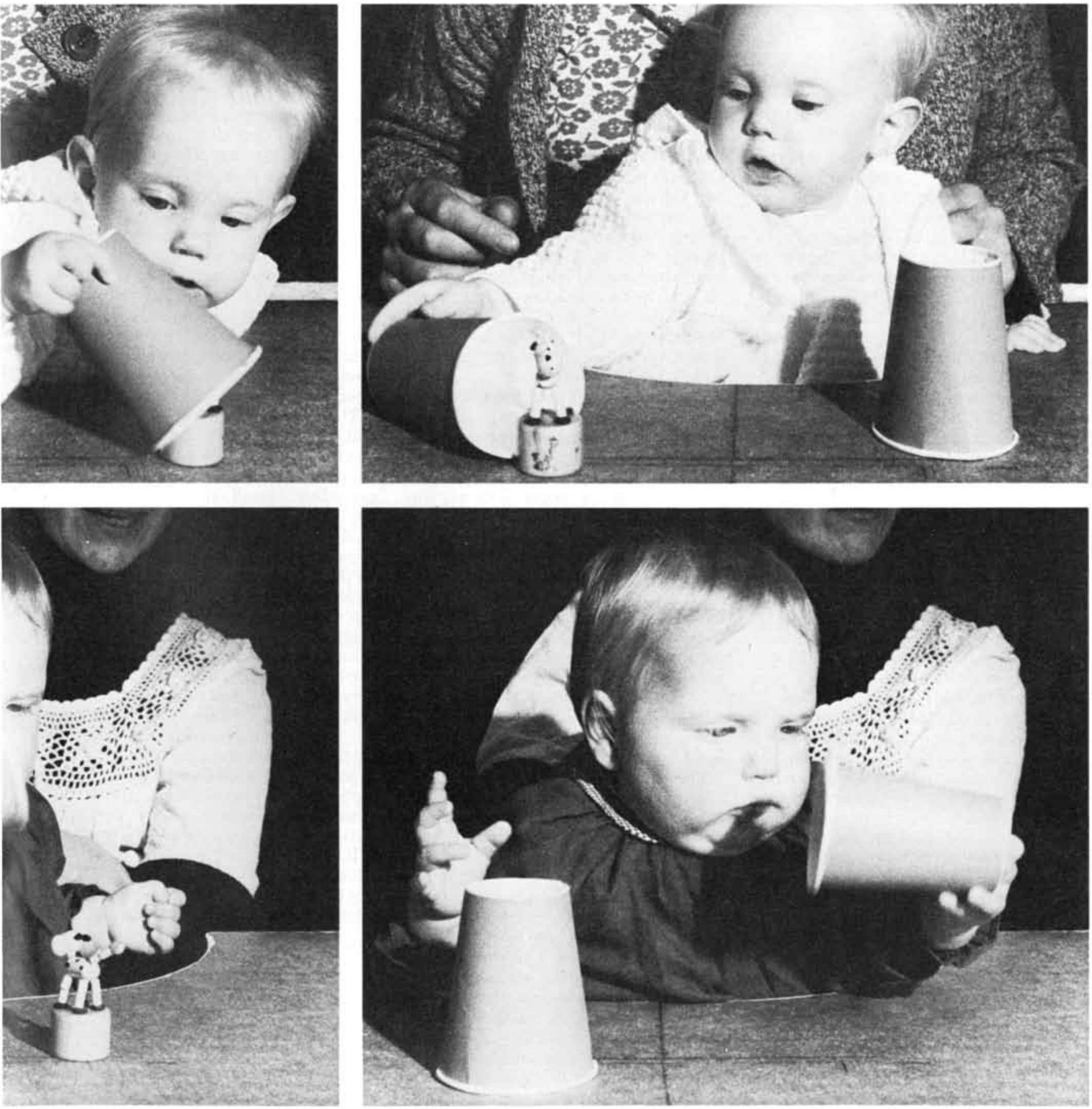


TRANSFER TASK makes use of the concept that one object can go inside another and still exist, acquired in the tracking task. An infant watches an adult place a toy under one of two cups and then is encouraged to choose the cup concealing the toy. A child with some tracking experience does very well (*three photographs at top*). A child with a great deal of tracking experience, however, does less well, al-

task that he is actually hampered by them when he is faced with a similar but not identical situation. An infant who has had less practice with tracking has the initial conceptual discovery (one object can go inside another and continue to exist) still at the front of his mind to help him perform the transfer task.

This kind of model of cognitive development can explain puzzling instances of repetitive processes in which young children give correct verbal responses to a problem whereas somewhat older children give incorrect responses. Here the underlying concept has been acquired late in infancy. When the verbal tests are first given, there has not been enough time for the initial discovery to have been specified to the extent that the child is incapable of applying the discovery to other situations. With older children, however, the initial discovery has been made highly specific. The relation between the initial problem and the new problem is therefore obscured. They must dredge the initial discovery from their memory, erring until they do, and they will seem to repeat an earlier phase of their cognitive development.

The various explanations of repetitive processes in development thus seem to differ depending on the specific repetition to be explained. What all the explanations have in common, however, is that they preserve the assumption that psychological growth, in spite of its apparent reversals and repetitions, is a continuous and additive process.



though he performs better than a child without tracking experience. In particular, if the child watches the toy being placed under the second cup after seeing it placed under the first cup a few times, he will still tend to look for it under the first cup (*three photographs at bottom*). Concept acquired in tracking task has become so specified with practice it actually hampers child in performing transfer task.

The Confinement of Quarks

How is it that these elementary particles of matter that explain so much about other particles are not seen? It may be that they are held inside other particles by forces inherent in their nature

by Yoichiro Nambu

An elementary particle of matter, strictly defined, is one that has no internal structure, one that cannot be broken up into smaller constituent particles. In the past decade or so it has become apparent that many particles long thought to be elementary, including such familiar ones as the proton and the neutron, are not elementary at all. Instead they appear to be composite structures made up of the more fundamental entities named quarks, in much the same way that an atom is made up of a nucleus and electrons.

The quark model amounts to an impressive simplification of nature. In the initial formulation of the theory there were supposed to be just three species of quark, and those three were enough to account for the properties of an entire class of particles with several dozen members. Every known member of that class could be understood as a combination of quarks; moreover, every allowed combination of the quarks gave rise to a known particle. The correspondence between theory and observation seemed too close to be coincidental, and experiments were undertaken with the aim of detecting the quarks themselves.

If the quarks are real particles, it seems reasonable that we should be able to see them. We know that the atom consists of a nucleus and a surrounding cloud of electrons because we can take the atom apart and study its constituents in isolation. We know that the nucleus in turn consists of protons and neutrons because the nucleus can be split into fragments and the constituent particles identified. It is easy to imagine a similar experiment in which particles thought to be made of quarks, such as protons, are violently decomposed. When that is attempted, however, the debris consists only of more protons and other familiar particles. No objects with the properties attributed to quarks are seen. Physicists have searched high and low, but free quarks have not been found.

It is possible, of course, that no experiment has yet looked in the right place or with the right instruments, but that now seems unlikely. It is also possible that the quarks simply do not exist, but physicists are reluctant to abandon a theory that carries such explanatory force. The successes of the theory represent compelling evidence that quarks exist inside particles such as the proton; on the other hand, the repeated failure of experimental searches to discover a free quark argues that the quarks do not exist independently. This paradox can be resolved, but only by making further theoretical assumptions about the quarks and the forces that bind them together. It must be demonstrated that quarks exist, but that for some reason they do not show themselves in the open. Theorists, who invented the quarks in the first place, are now charged with explaining their confinement within the particles they make up.

The particles thought to be made up of quarks are those called hadrons; they are distinguished by the fact that they interact with each other through the strong force, the force that binds together the particles in the atomic nucleus. ("Hadron" is derived from the Greek *hadros*, meaning stout or strong.) No other particles respond to the strong force.

The hadrons are divided into the two large subgroups named the baryons and the mesons. These two kinds of particle differ in many of their properties, and indeed they play different roles in the structure of matter, but the distinction between them can be made most clearly in the context of the quark model. All baryons consist of three quarks, and there are also antibaryons consisting of three antiquarks. The proton and the neutron are the least massive and the most familiar of the baryons. Mesons have a different structure: they consist of a quark bound to an antiquark. The pi meson, or pion, is the least massive of the mesons.

The properties of the hadrons can perhaps be best illustrated by considering them in contrast with the remaining major group of particles: the leptons. The leptons are not susceptible to the strong force (or else they would be hadrons). There are just four of them: the electron, the muon, the electron-type neutrino and the muon-type neutrino (along with the four corresponding antiparticles). The leptons seem to be truly elementary: they have no internal structure. Indeed, they apparently have no size. They can be represented as dimensionless points, so that it would not seem possible for them to have an internal structure.

The hadrons differ from the leptons in many respects, and they give several clues to their composite nature. The hadrons have a finite size, even if it is exceedingly small: about 10^{-13} centimeter. Experiments in which protons or neutrons collide at high energy with other particles give fairly direct evidence of an internal structure: electric and magnetic fields and the field associated with the strong force all seem to emanate from point sources within the particles. Finally, there are a great many hadrons. Well over 100 are known, most of them very short-lived, and there is every indication that many more exist and have not yet been observed only because the particle accelerators available today cannot supply enough energy to create them. There is no obvious limit to the number of hadrons that might be found as larger accelerators are built.

It was the great multiplicity of the hadrons that led to the formulation of the quark model. Without some organizing principle such a large collection of particles seemed unwieldy, and the possibility that they might all be elementary offended those who hold the conviction, or at least the fond wish, that nature should be simple. The quark hypothesis replaced the great variety of hadrons with just three fundamental building blocks from which all the hadrons could be constructed. It was proposed in 1963, independently by Murray Gell-Mann and George Zweig, both of the California Institute of Technology. It was Gell-Mann who supplied the name quark, from a line in James Joyce's *Finnegans Wake:* "Three quarks for Muster Mark!"

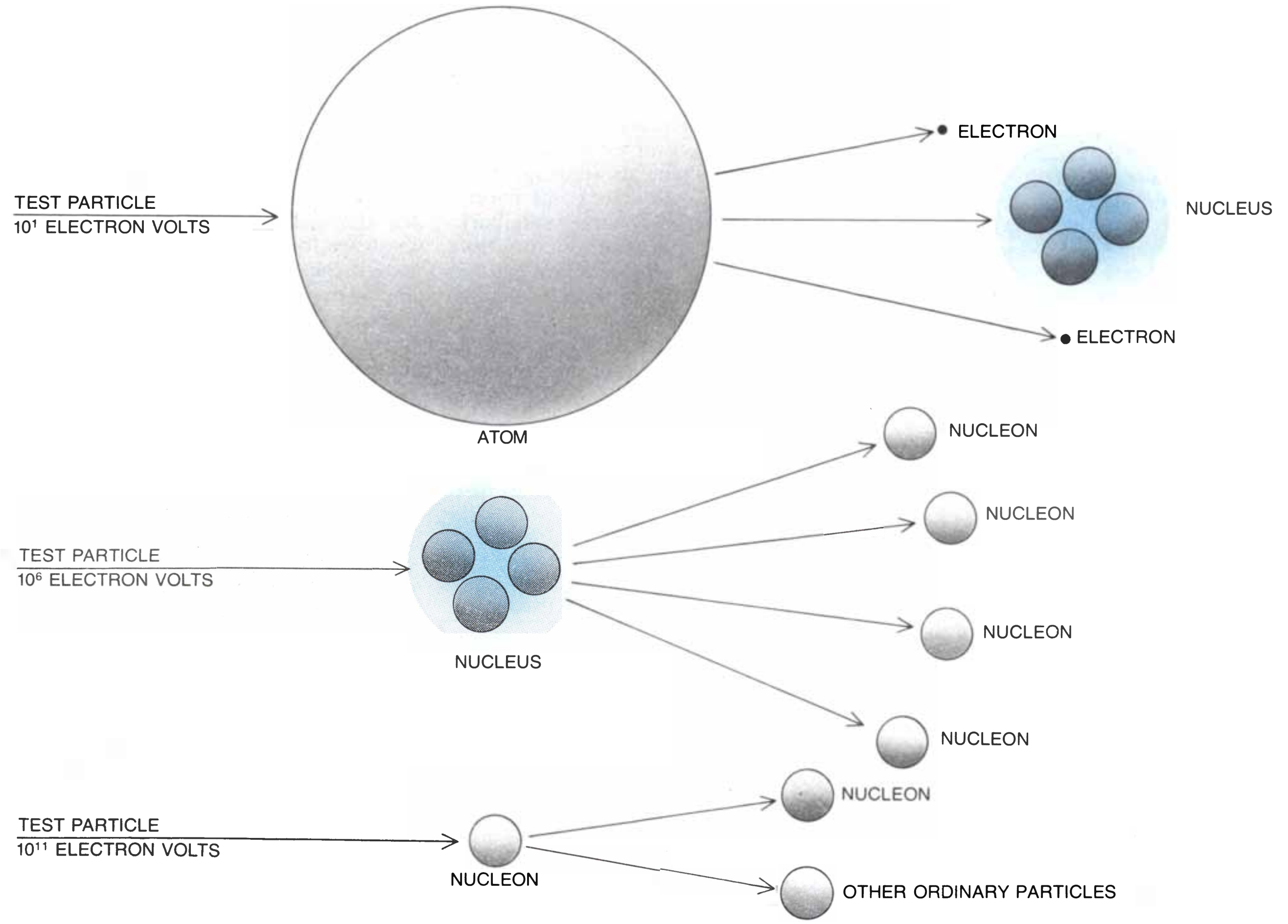
The immediate inspiration for the quark hypothesis was the discovery, made by Gell-Mann and by Yuval Ne'eman of Tel-Aviv University, that all the hadrons can be grouped logically in families of a few members each. The mesons form families of one particle and of eight particles; the baryons form families of one, eight and 10.

The classification of particles is made easier by tabulating their properties in numerical form. Each number refers to a single property, and it can assume only certain discrete values. Since the numbers are assigned in discrete units, or quanta, they are called quantum numbers. A complete list of a particle's quantum numbers identifies it uniquely and defines its behavior.

Electric charge is a typical quantum number. The fundamental unit of measurement is the electric charge of the proton or the electron, and in those units the charges of all observed particles can be expressed as simple integers (such as 0, +1 and −1). Another quantum number is called baryon number. Baryons are arbitrarily assigned a value of +1 and antibaryons a value of −1. Mesons have a baryon number of 0. Strangeness, the property of hadrons introduced in the 1950's to explain the strangely long lifetimes of some massive particles, is also accounted for through a quantum number with only integer quantities.

One of the most important quantum numbers is spin angular momentum. Under the rules of quantum mechanics a particle's state of rotation is one of its intrinsic properties, and the particle must therefore always have a specified and unvarying angular momentum. (The angular momentum is measured in units of Planck's constant divided by 2π, Planck's constant being 6.6×10^{-27} erg-second.) A crucial distinction is made between particles whose spins have a half-integer value (that is, half an odd integer, such as 1/2 or 3/2) and those with integer spin (such as 0, 1 or 2). As we shall see, this distinction determines the behavior of the particles when they are brought together in a bound system, but for now it is enough to note that all baryons have half-integer spins and all mesons have integer spins.

The families of hadrons defined by Gell-Mann and Ne'eman are related by spin angular momentum. All the members of a given family have the same quantity of spin. Within the families the members are distinguished from one another by two other quantum numbers: isotopic spin and hypercharge. In spite of its name, isotopic spin has nothing to



STRUCTURE OF MATTER has been examined at progressively finer scale by a process of violent decomposition. The atom can be reduced to its component parts by striking it with a projectile carrying relatively little energy: a few electron volts. This is the process called ionization, and in the extreme case it results in the isolation of free electrons and a nucleus. The nucleus can also be dismembered, although higher energy is required. The nucleus splits into free protons and neutrons, which are collectively called nucleons. Nucleons in turn seem to be composed of the pointlike entities called quarks, and it would seem that the quarks might be liberated by smashing a nucleon with a test particle of sufficient energy. When that experiment is attempted, however, free quarks are not seen, even at the highest energies now attainable (a few hundred billion electron volts). Instead other ordinary particles are created, including many that are thought to be made up of quarks. A possible explanation of this effect is that the quarks are permanently confined within the nucleon.

do with angular momentum; it is determined by the number of particles included in a given group. Hypercharge is determined by the electric charges of those particles, and it is also related to both baryon number and strangeness. From the various possible combinations of the values that these two quantum numbers can assume it is possible to construct an array for each family of hadrons. These arrays, having in each case one, eight or 10 positions, predict the existence of all the known hadrons and of no others. The formation of these arrays can be described formally in the branch of mathematics called group theory. The arrays are said to be representations of the symmetry group SU(3), which stands for special unitary group for matrixes of size 3×3.

The quarks are also described by an SU(3) symmetry group. Gell-Mann designated the quarks by the arbitrary labels *u*, *d* and *s*, for "up," "down" and "sideways." All of them have the same spin angular momentum, 1/2 unit, and in the SU(3) group they form a family of their own; it is, obviously, a family of three. The three members of the quark family are distinguished by having different values of isotopic spin and hypercharge, and they differ in other quantum numbers as well. The electric charges assigned to them are particularly unusual. The *u* quark has a charge of +2/3, and the *d* quark and the *s* quark each have a charge of −1/3. The baryon numbers of the quarks are also fractional: all the quarks have a baryon number of +1/3. Strangeness, on the other hand, remains an integer quantum number; the *u* and *d* quarks have zero strangeness and the *s* quark has a strangeness of −1. For the corresponding antiquarks, whose symbols are $\bar{u}$, $\bar{d}$ and $\bar{s}$, the magnitude of each of these quantum numbers is the same but the sign is changed.

The fundamental rule for the construction of hadrons from quarks is disarmingly simple: it states that all the quantum numbers of the hadron can be found by adding up the quantum numbers of the constituent quarks. The proton, for example, consists of two *u* quarks and one *d* quark, a configuration written *uud*. The electric charges are therefore $2/3 + 2/3 - 1/3$, for a total value of +1. The baryon number is $1/3 + 1/3 + 1/3$, or +1, and since the strangeness of each of these quarks is zero, the total is also zero. All the sums are in accord with the measured properties of the proton.

The positively charged pi meson is made up of a *u* quark and a $\bar{d}$ antiquark. The electric charges of the quarks are +2/3 and +1/3, for a total of +1, and the baryon numbers are +1/3 and −1/3, for the total baryon number of zero required of a meson. The strangeness again is zero. The spin-angular-momentum quantum number calls for a slightly more elaborate calculation because the spins of the quarks can be aligned in either of two ways, and the alignment determines the signs that must be supplied for the spin quantum numbers when they are summed. In all possible cases, however, combinations of three quarks or three antiquarks (baryons and antibaryons) must have half-integer spin, whereas combinations of a quark and an antiquark (mesons) must have integer spin.

The great strength of the quark model is that through this simple additive procedure the model correctly predicts all the quantum numbers of the known hadrons. In particular it should be pointed out that all allowed combinations of the quarks yield integer values of electric charge and baryon number, and that no other combinations do so (except in the trivial case of multiples of the allowed combinations). Furthermore, all the known hadrons can be constructed out of either three quarks or a quark and an antiquark.

In the past few years it has become apparent that there may be a fourth species of quark, bearing a new quantum number somewhat similar to strangeness and given the arbitrary name charm. The new quark (labeled *c*) adds another dimension to the symmetry group that describes the hadrons, and it predicts the existence of a multitude of new particles, some of which may already have been found. The addition of charm to the quark model, which seems increasingly to be justified by the experimental evidence, has a number of attractive features and can be considered to strengthen the model, but it has little effect on the problem of quark confinement.

In many respects quarks are like leptons. Both kinds of particle can apparently be represented as dimensionless points, and if they are without extension, they are also presumably without internal structure. All the quarks and all the leptons also share the property of having a spin of 1/2 unit. Finally, if the charm hypothesis is correct, then there are four members of each group; indeed, the appeal of that symmetry was one of the principal motivations for introducing the concept of charm. (On the other hand, four need not be the ultimate number of quarks and leptons. Both groups could have additional, undiscovered members.)

The resemblance between quarks and leptons is not a superficial one, but there are important differences between these two kinds of fundamental particle. In the first place, quarks participate in strong interactions, whereas leptons do not. The quarks also form aggregations of particles (hadrons), whereas there are no analogous composite structures made up of leptons. Why is it, however, that the quarks form only certain well-defined aggregations, those made up either of three quarks or of a quark and an antiquark? Many other combinations are conceivable—four quarks, two quarks, a quark and two antiquarks, even states made up of hundreds or thousands of quarks—but there is no evidence that any of them exist. A state of particular interest is the one represented by a solitary quark. Isolated leptons are commonplace; what distinguishing property of quarks prohibits them from appearing in isolation?

The concept that has provided the first, speculative answers to these questions was introduced in order to mend a conspicuous flaw in the quark theory.

		SPIN (J)	ELECTRIC CHARGE (Q)	BARYON NUMBER (B)	STRANGENESS (S)	CHARM (C)
QUARKS	u (UP)	½	+⅔	⅓	0	0
	d (DOWN)	½	−⅓	⅓	0	0
	s (STRANGE)	½	−⅓	⅓	−1	0
	c (CHARMED)	½	+⅔	⅓	0	+1
ANTIQUARKS	$\bar{u}$ (UP)	½	−⅔	−⅓	0	0
	$\bar{d}$ (DOWN)	½	+⅓	−⅓	0	0
	$\bar{s}$ (STRANGE)	½	+⅓	−⅓	+1	0
	$\bar{c}$ (CHARMED)	½	−⅔	−⅓	0	−1

PROPERTIES OF QUARKS are accounted for by assigning them quantum numbers, which can assume only certain discrete values. In the original quark model there were three kinds of quark, labeled *u* and *d* (for "up" and "down") and *s* (for "sideways" or "strange"). There is now evidence for a fourth quark species, labeled *c* (for "charm"). The quarks have fractional electric charge and fractional values of baryon number, a quantum number that distinguishes between two groups of particles. The spin quantum number reflects the intrinsic angular momentum of the quarks; the strangeness and charm quantum numbers recognize special properties of *s* and *c* quarks respectively. For each quark there is an antiquark with opposite quantum numbers.

The flaw involves an apparent conflict between the behavior of the quarks and one of their quantum numbers, spin angular momentum. The assignment of a spin of 1/2 unit to each of the quarks is essential if the spins of the hadrons are to be predicted correctly. Quantum mechanics, however, specifies rules for the behavior of particles with half-integer spins, and the quarks do not seem to obey them.

The quantum-mechanical rules postulate a connection between the spin of a particle and its "statistics," the set of rules that mandates how many identical particles can occupy a given state. Particles with integer spin are said to obey Bose-Einstein statistics, which allow an unlimited number of particles to be brought together in one state. Particles with half-integer spins obey Fermi-Dirac statistics, which require that no two identical particles occupy a state. This is the exclusion principle formulated by Wolfgang Pauli, the quantum-mechanical equivalent of the intuitive notion that no two things can be in the same place at the same time.

The most familiar application of Fermi-Dirac statistics and of the related exclusion principle is in atomic physics. There it governs the way electrons (which, being leptons, have a spin of 1/2) fill the orbitals, or energy levels, surrounding the nucleus. If an orbital contains one electron, one more can be added, provided that its spin is aligned in the direction opposite to that of the first electron's. With opposite spins the electrons do not have identical quantum numbers, and so they can occupy the same state, in this case an atomic orbital. Since there are only two possible directions for the spin, however, all other electrons are permanently excluded from the orbital.

The connection between spin and statistics is not well understood at a theoretical level, but it is not in doubt. In fact, formal proofs have been presented showing that the exclusion principle must be obeyed by all particles with half-integer spin, without exception. Like electrons, quarks move in orbitals, although their motion is measured not with respect to a nucleus but with respect to one another or to their common center of mass. For the least massive families of hadrons all the quarks should be in the same orbital: the smallest one. It follows that no two quarks in a hadron can have exactly the same quantum numbers.

In the quark model of the meson the requirements of Fermi-Dirac statistics can readily be accommodated. The two particles that compose a meson are a quark and an antiquark, and their quantum numbers are therefore different (in some cases they are exactly opposite). In the baryon, however, spin and statistics issue conflicting imperatives. In at least three baryons (*uuu, ddd* and *sss*) all three quarks have identical quantum numbers. Because there are three particles in the baryon, at least two of them must have their spins aligned the same way, and in many cases all three spins must point in the same direction. The exclusion principle seems to be violated.

QUARK FLAVORS	QUARK COLORS: RED	GREEN	BLUE
u (UP)	$Q = +\frac{2}{3}$, $B = +\frac{1}{3}$	$Q = +\frac{2}{3}$, $B = +\frac{1}{3}$	$Q = +\frac{2}{3}$, $B = +\frac{1}{3}$
	$Q = 0$, $B = 0$	$Q = +1$, $B = 0$	$Q = +1$, $B = +1$
d (DOWN)	$Q = -\frac{1}{3}$, $B = +\frac{1}{3}$	$Q = -\frac{1}{3}$, $B = +\frac{1}{3}$	$Q = -\frac{1}{3}$, $B = +\frac{1}{3}$
	$Q = -1$, $B = 0$	$Q = 0$, $B = 0$	$Q = 0$, $B = +1$
s (STRANGE)	$Q = -\frac{1}{3}$, $B = +\frac{1}{3}$	$Q = -\frac{1}{3}$, $B = +\frac{1}{3}$	$Q = -\frac{1}{3}$, $B = +\frac{1}{3}$
	$Q = -1$, $B = 0$	$Q = 0$, $B = 0$	$Q = 0$, $B = +1$
c (CHARM)	$Q = +\frac{2}{3}$, $B = +\frac{1}{3}$	$Q = +\frac{2}{3}$, $B = +\frac{1}{3}$	$Q = +\frac{2}{3}$, $B = +\frac{1}{3}$
	$Q = 0$, $B = 0$	$Q = +1$, $B = 0$	$Q = +1$, $B = +1$

ADDITIONAL QUANTUM NUMBER of quarks is called color, and it can assume three possible values, represented here by the primary colors red, green and blue. In contrast to color the original quark designations *u, d, s* and *c* are sometimes called quark flavors. (Both color and flavor are arbitrary terms; they do not have their usual meaning.) Each flavor of quark is assumed to exist in each of the three colors. In one model (*white boxes*) red, green and blue quarks of a given flavor are indistinguishable; they have the same values of electric charge (*Q*) and baryon number (*B*) and of all other quantum numbers. In an alternative theory (*gray boxes*) proposed by the author and M.-Y. Han quarks of different colors differ in electric charge and baryon number, and these quantum numbers can be given integer values. The Han-Nambu model cannot be excluded with certainty, but in this article fractional charges are assumed.

A strategy for avoiding this uncomfortable conclusion was first proposed by O. W. Greenberg of the University of Maryland. Greenberg suggested that the quarks might not obey Fermi-Dirac statistics but could instead be governed by an unconventional set of rules he called para-Fermi statistics of order 3. Whereas in Fermi-Dirac statistics a state can be occupied by only one particle, in para-Fermi statistics it can be occupied by three particles, but no more.

Another approach to the problem was later suggested by M.-Y. Han of Duke University and me, and independently by A. Tavkhelidze of the Joint Institute for Nuclear Research in the U.S.S.R. and Y. Miyamoto of the Tokyo University of Education. Instead of changing the rules we changed the quarks. By assigning each quark an extra quantum number with three possible values, it is possible to arrange for all the quarks in a baryon to be of different species and therefore in different quantum-mechanical states. All that is necessary is some mechanism that will ensure that in every case each quark has a different value of the new quantum number. This extra quantum number has come to be known as color. For the three values of the quantum number it is convenient to adopt the three primary colors red, green and blue; the antiquarks have anticolors, which can be represented by the complements of the primaries, respectively cyan, magenta and yellow. (None of these terms, of course, has any connection with its conventional meaning; they are arbitrary labels.)

The para-Fermi statistics can be regarded as a special case of the color hypothesis. The two theories are equivalent if the assumption is that color is completely unobservable. In that case quarks of different colors would appear to be identical in all their properties, and since there would be no way of telling one from another it would seem that identical quarks were obeying unconventional statistics. Color would be invisible, or, to put it another way, nature would be color-blind. The color hypothesis allows, however, for the possibility that color might be visible under some circumstances.

The introduction of color necessarily triples the number of quarks. If only the original three quarks are considered, then with color there is a total of nine; if the charmed quark is included, it too must have red, green and blue varieties, and the total number of quarks is 12. The number of hadrons, however, is not increased; the color hypothesis does not predict any new particles. The number of hadrons is unchanged because of the special way the colors are allotted to the quarks in a hadron. If the colors are to solve the problem of quark statistics, it is essential that a baryon contain one quark of each color; if a baryon could be made of three red quarks, for example, then the quantum numbers of all the quarks could well be identical. Only if all three colors are equally represented can obedience to the exclusion principle be ensured. Since we have assigned the quarks primary colors such a combination could be termed white, or colorless. As we shall see, the theory implies that all hadrons, both baryons and mesons, are colorless. The baryons are made up of equal quantities of red, green and blue; the mesons are equal mixtures of each color with its anticolor.

The formal treatment of the quark colors involves postulating another SU(3) symmetry group, exactly analogous to the one that determines the other properties of the quarks. The two quantum numbers that determine the quark colors are named, again by analogy to the original SU(3) group, color isotopic spin and color hypercharge. The properties determined by the original SU(3) symmetry are sometimes called quark flavors, and flavor, unlike color, is readily observed in experiments; it is, as it were, tasteable. The labels *u, d, s* and *c* represent the quark flavors, and they determine all the observable properties, such as electric charge, of the hadrons they compose. The symmetry among the flavors is not a perfect one, and quarks that differ in flavor have slightly different masses. Color, on the other hand, is an exact symmetry; in the usual formulation of the theory a quark of a given flavor has the same properties and the same mass regardless of its color.

Color was introduced into the quark theory as an ad hoc element to solve the problem of quark statistics. It has since become a central feature of the model. In particular it is thought to determine the forces that bind quarks together inside a hadron, and hence to have a profound influence on quark confinement. In this context the qualitative distinction between quarks and leptons begins to seem comprehensible. An important element in the distinction is that leptons do not form strongly bound states. If it is the color quantum number that is responsible for binding quarks together, then the absence of strong binding in leptons is readily understood, since the leptons do not have color.

In order to understand the forces between quarks it is helpful to consider first a more familiar force: electromagnetism. The electromagnetic force is described by Coulomb's law, which states that the force between two charged bodies declines as the square of the distance between them. For example, the force between a proton in the nucleus of an atom and one of the electrons surrounding the nucleus is described by this law. The force can be regarded as being transmitted by a field or by discrete particles: photons, the quanta of the electromagnetic field. Ultimately both the field and the force are derived from the electric charges of the particles; since those charges are unlike, the force is attractive.

The forces between quarks are in many respects similar, but they are somewhat more complicated. In the case of the electromagnetic field only one quantum number (electric charge)

PROPERTIES	CONSTITUENT QUARKS u		 u		 d		HADRONS PROTON (p)
SPIN (J)	(½,½)	+	(½,½)	+	(½,−½)	=	(½,½)
ELECTRIC CHARGE (Q)	⅔	+	⅔	−	⅓	=	+1
BARYON NUMBER (B)	⅓	+	⅓	+	⅓	=	+1
STRANGENESS (S)	0	+	0	+	0	=	0
CHARM (C)	0	+	0	+	0	=	0

			u		$\bar{d}$		PION (π^+)
SPIN (J)			(½,½)	+	(½,−½)	=	(0,0)
ELECTRIC CHARGE (Q)			⅔	+	⅓	=	+1
BARYON NUMBER (B)			⅓	−	⅓	=	0
STRANGENESS (S)			0	+	0	=	0
CHARM (C)			0	+	0	=	0

	$\bar{u}$		$\bar{d}$		$\bar{d}$		ANTINEUTRON ($\bar{n}$)
SPIN (J)	(½,−½)	+	(½,½)	+	(½,½)	=	(½,½)
ELECTRIC CHARGE (Q)	−⅔	+	⅓	+	⅓	=	0
BARYON NUMBER (B)	−⅓	−	⅓	−	⅓	=	−1
STRANGENESS (S)	0	+	0	+	0	=	0
CHARM (C)	0	+	0	+	0	=	0

	u		d		s		LAMBDA (Λ^0)
SPIN (J)	(½,½)	+	(½,−½)	+	(½,½)	=	(½,½)
ELECTRIC CHARGE (Q)	⅔	−	⅓	−	⅓	=	0
BARYON NUMBER (B)	⅓	+	⅓	+	⅓	=	+1
STRANGENESS (S)	0	+	0	−	1	=	−1
CHARM (C)	0	+	0	+	0	=	0

			c		$\bar{u}$		CHARMED MESON (D^0)
SPIN (J)			(½,½)	+	(½,−½)	=	(0,0)
ELECTRIC CHARGE (Q)			⅔	−	⅔	=	0
BARYON NUMBER (B)			⅓	−	⅓	=	0
STRANGENESS (S)			0	+	0	=	0
CHARM (C)			1	+	0	=	+1

QUARKS COMBINE to make up the class of observed particles called hadrons. Two kinds of quark combination are possible. In one of them three quarks bind together to form a baryon (such as the proton) or three antiquarks bind to form an antibaryon (such as the antineutron). In the other kind of quark binding a quark and an antiquark make up a meson (such as the pion). The properties of these hadrons are determined by the simple rule that the quantum numbers of the hadron are the sums of the quark quantum numbers. All the allowed combinations of quarks give integer values of electric charge. The baryon numbers add in such a way that all baryons have a value of +1, antibaryons −1 and mesons 0. Strange particles, such as the lambda baryon, are those that have at least one *s* quark; charmed particles have at least one *c* quark. The spin quantum number is a vector and requires a more complicated arithmetic, but the result of the addition is that all baryons and antibaryons have half-integer spin and all mesons have integer spin. The great success of the quark theory is that all the allowed combinations yield known hadrons and no other combinations do so. The problem of quark confinement is why only these combinations should exist, and why solitary quarks are not observed.

is involved in generating the field; the fields between quarks are generated by two quantum numbers: color isotopic spin and color hypercharge. To continue the analogy with electromagnetism, these quantum numbers can be regarded as two varieties of "color charge."

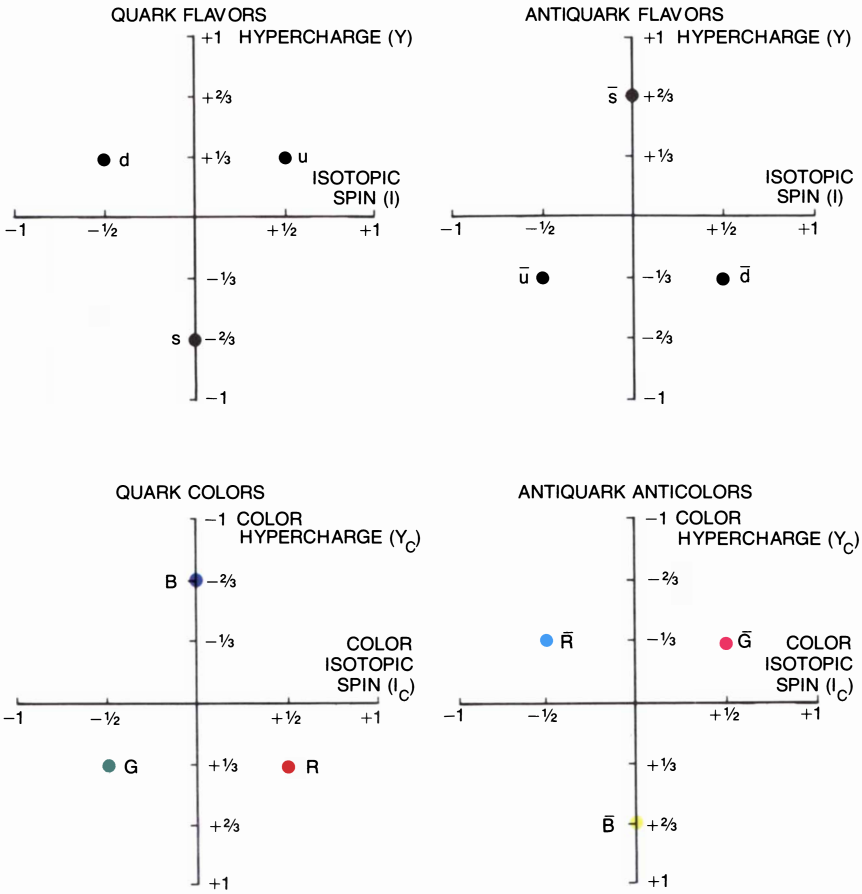
If a combination of quarks is to be stable, it is obvious that the forces between them must be attractive. That can be arranged by ensuring that the quarks in a baryon, for example, are all of different colors, since the quarks will then have unlike values of the two kinds of color charge. A red quark and a green quark will be bound together because their color-isotopic-spin numbers are of opposite sign; the blue quark will be bound to both of the others because of a difference in the sign of the color-hypercharge quantum number. A similar mechanism generates an attractive force between a quark of one color and an antiquark of the corresponding anticolor, as in a meson. The forces favor just those combinations that have been identified as white, or colorless.

Actually the situation is still more complicated. Whereas the electromagnetic force is transmitted by a single kind of particle, the photon, the force associated with quark colors requires eight fields and eight intermediary particles. These particles have been named gluons because they glue the quarks together. Like the photon, all of them are massless and have a spin of 1; like the quarks themselves, they have not been detected as free particles.

The eight gluons can be regarded as having composite colors, made up of the various combinations of three colors and three anticolors. All together there are nine such combinations, but one of them receives equal contributions from red combined with antired, green combined with antigreen and blue combined with antiblue. Since that combination is effectively colorless it is a trivial case and is excluded, leaving eight colored gluons.

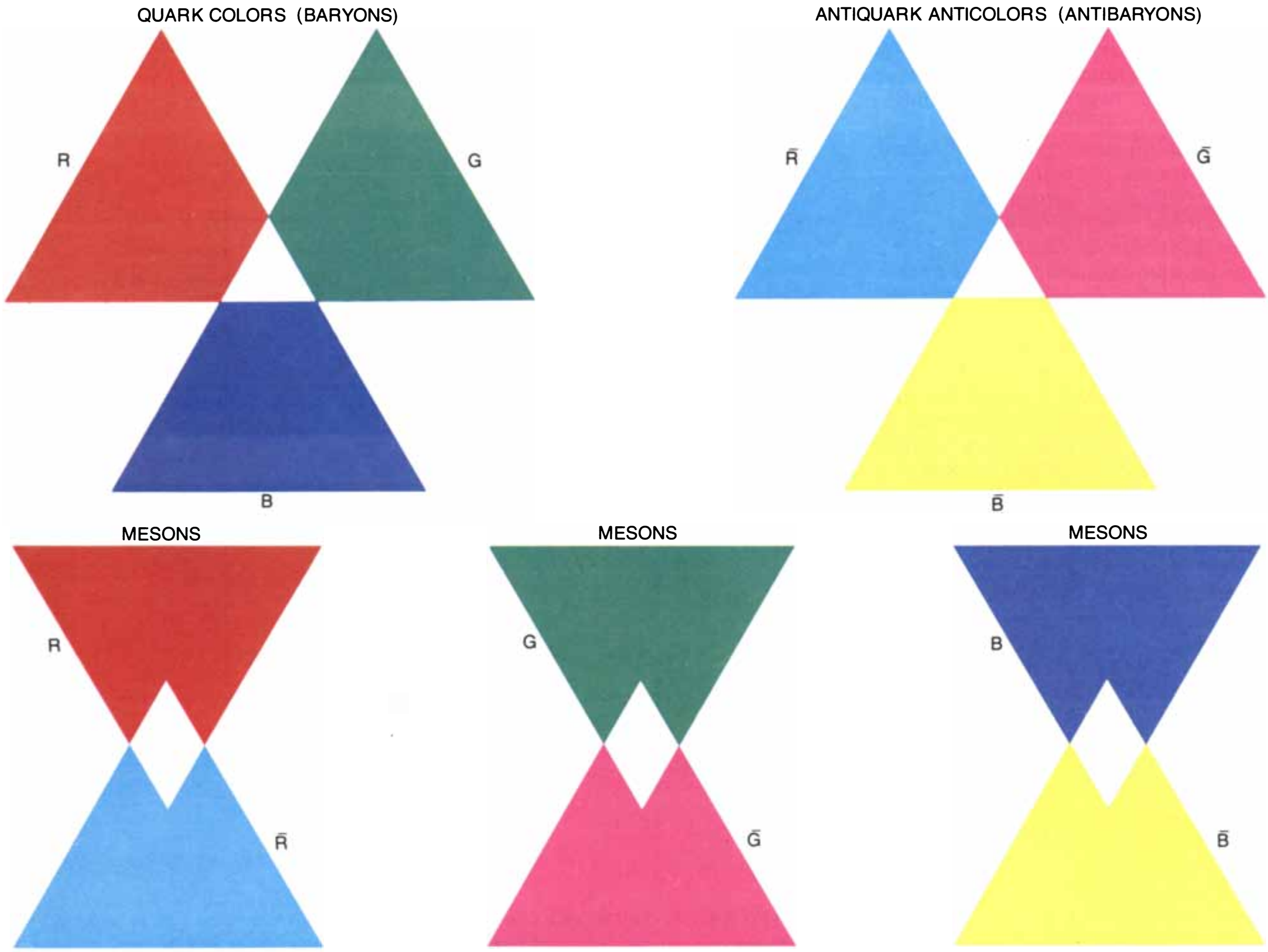
Quarks interact by the exchange of gluons; when they do so, they can change their colors but not their flavors. At all times a baryon contains red, green and blue quarks, but because gluons are continually exchanged it is not possible to say at any given moment which quark is which color. Similarly, a meson always consists of a quark of one color and an antiquark of the complementary anticolor, but the three possible combinations of color and anticolor are equally represented. In quantum mechanics we can have no certain knowledge of quark colors; rather, we can know only the probability that a quark is a given color. If all hadrons are colorless, the probabilities for the three colors are equal.

The model of hadrons in which these

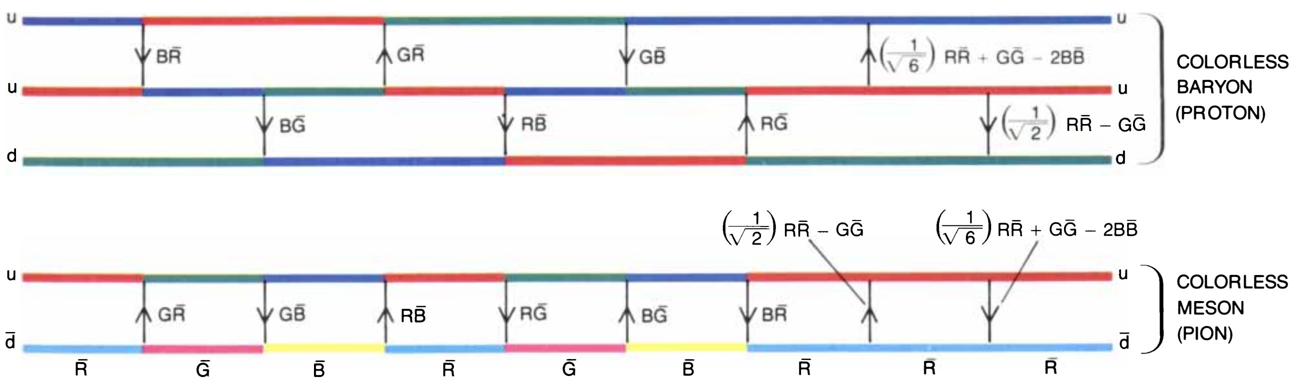


CLASSIFICATION OF QUARKS is governed by a fundamental symmetry of nature. The quark flavors are determined by two quantum numbers, isotopic spin and hypercharge; each quark or antiquark represents a unique combination of these numbers. Color is determined by two other quantum numbers, named by analogy color isotopic spin and color hypercharge. Both flavor and color can be described by means of the concept of a symmetry group. Flavor is a "broken symmetry" because quarks with different flavors differ in properties such as mass and electric charge. Color is an exact symmetry: two quarks of the same flavor but of different colors differ only in their colors and are otherwise indistinguishable. The quark colors are thought to generate forces binding quarks together. These forces result from two kinds of field, or color charge, associated with quantum numbers color isotopic spin and color hypercharge.

COLORED GLUONS are the particles that transmit forces between colored quarks; they are the quanta of the fields generated by the color quantum numbers just as the photon is the quantum of the electromagnetic field. The gluons can be regarded as combinations of color and anticolor. In the first analysis there are nine possible combinations of three colors and three anticolors; six of these combinations (*white squares*) are straightforward but three require special treatment (*gray squares*). The three involve combinations of a single color with the corresponding anticolor, and in each combination all quantum numbers cancel out. States with null quantum numbers can be combined at will, but only three of these combinations of combinations need be considered. One is $R\bar{R} + G\bar{G} + B\bar{B}$, in which the quantum numbers are still null; the case is trivial and can be eliminated. The remaining two are $R\bar{R} - G\bar{G}$ and $R\bar{R} + G\bar{G} - 2B\bar{B}$, which can be treated like the other six gluons except that numerical correction factors are required.



COLORLESS HADRONS are formed by properly combining the colored quarks. A baryon consists of three quarks, one each of red, green and blue color. (The quarks can have any flavor, and their flavors determine all the observable properties of the particle.) Similarly, an antibaryon is made up of three antiquarks having each of the three anticolors. The anticolors are shown here as the complements of the corresponding primary colors. In mesons the colors and anticolors are equally represented. In each of these combinations the net color quantum numbers are zero; in figurative terms the hadrons are white or colorless. No other combinations of colors can give the same result. It is thus possible to explain why only these combinations of quarks exist in nature, and why single quarks are prohibited, by postulating that only colorless particles are observable. The problem of quark confinement is then reduced to the problem of explaining this postulate.



EXCHANGE OF GLUONS binds together the quarks in a hadron and can simultaneously change their colors. In these diagrams the vertical dimension represents the spatial separation between the quarks and the horizontal dimension represents time. At each vertex where a gluon is emitted or absorbed the color quantum numbers must balance. Hence at the upper left, where a blue quark emits a blue-antired gluon, the "bluishness" of the quark is carried off by the gluon, and the quark changes to red, balancing the antired of the gluon. When the gluon is absorbed, the antired of the gluon and the red of the absorbing quark annihilate each other, and the quark is left with a net color of blue. The gluons at the far right, which have null quantum numbers, do not change the quark colors, and no gluons have any effect on quark flavors. At all times the baryon contains a red, a green and a blue quark; in the meson the color of the quark is balanced at each of the instants shown here by the anticolor of the antiquark. In practice it is not possible to determine the colors of the quarks; only the probability of each color can be calculated. In hadrons that are colorless the probabilities of the colors are equal.

particles are composed of quarks bound together by the exchange of gluons can be given an elegant mathematical formulation. The model is an example of a non-Abelian gauge theory, a kind of theory invented by C. N. Yang of the State University of New York at Stony Brook and Robert L. Mills of Ohio State University. A gauge theory is one modeled on the theory of electromagnetism developed by James Clerk Maxwell. A characteristic of such theories is that any particle carrying a given quantum number, or charge, generates a long-range field whose strength is proportional to the quantum number. In Maxwell's theory the quantum number in question is electric charge; in the model of hadron structure there are two such numbers, those associated with the quark colors.

Maxwell's theory is an Abelian gauge theory; non-Abelian gauge theories are distinguished from it by the fact that the fields themselves carry quantum numbers. A field can therefore act as a source of itself. Einstein's theory of gravitation is also a non-Abelian gauge theory in that the gravitational field itself generates gravity. Electromagnetism and the weak force, which is responsible for certain kinds of radioactive decay, have recently been combined in another non-Abelian gauge theory by Steven Weinberg of Harvard University and by Abdus Salam of the International Centre for Theoretical Physics in Trieste. The colored-quark model could now provide a similar framework for understanding the strong force. These four forces—strong, weak, electromagnetic and gravitational—are the only ones known in nature. It would bring great aesthetic satisfaction if all four could be understood through the same kind of theory.

Before describing schemes for the confinement of quarks it would be well to consider the possibility that they are not confined at all. Perhaps they have been there all the time but we have not been able to detect their presence, or perhaps we have confused them with some ordinary particle. If a fractionally charged quark could escape from a hadron, it would almost certainly be stable in isolation. One quark might decay to yield another quark, perhaps along with some ordinary particles, but at least one quark species—the one with the smallest mass—must be stable. It could not decay because all particles other than quarks have integer charges, which cannot be created from the decay of a fractionally charged quark.

Such free, stable quarks could well come to rest among the atoms of ordinary matter. Similarly, if they can escape, they should be found in the debris produced by high-energy collisions of hadrons, both in particle accelerators and when cosmic rays collide with atoms in the atmosphere. The principal argument against the existence of such free quarks is that they have not been found in ordinary matter, even in minute concentrations, and they have not been seen in the aftermath of hadron collisions.

If fractionally charged quarks were present, they could readily be detected and recognized. Charged particles are detected by the ionization they cause in the atoms surrounding them. The extent of the ionization is proportional to the square of the particle's electric charge. Thus a quark with a charge of 1/3 would produce only one-ninth the ionization of a particle with a charge of 1, and it could easily be distinguished from ordinary particles.

Perhaps, however, the quarks do not have fractional charges. With the addition of color to the quark theory it becomes possible to assign each quark integer values of both electric charge and baryon number, and Han and I proposed such a model in 1965. The model has the effect of making color visible, in the sense that quarks of different colors carry different masses, electric charges and baryon numbers and can therefore be distinguished. For each flavor of quark all the electric charge ($+1$ or -1) would be assigned to one color, and the other two colors would have zero charge. If all colors must be represented equally, then the total charge of the hadron would be correct. If the quarks do have integer charges, then a free quark in the laboratory would not look much different from an ordinary baryon and might easily be misidentified. This possibility cannot yet be excluded with certainty.

Another hypothesis suggests that it is difficult to extract quarks from hadrons, but not impossible. Perhaps they are simply very massive and the accelerators operating today are not powerful enough to liberate them. That hypothesis, however, requires that the mass of a free quark and that of a bound quark be quite different. Indeed, a single isolated quark might be more massive than a baryon composed of three quarks, a notion that is difficult to understand if it is not inconceivable.

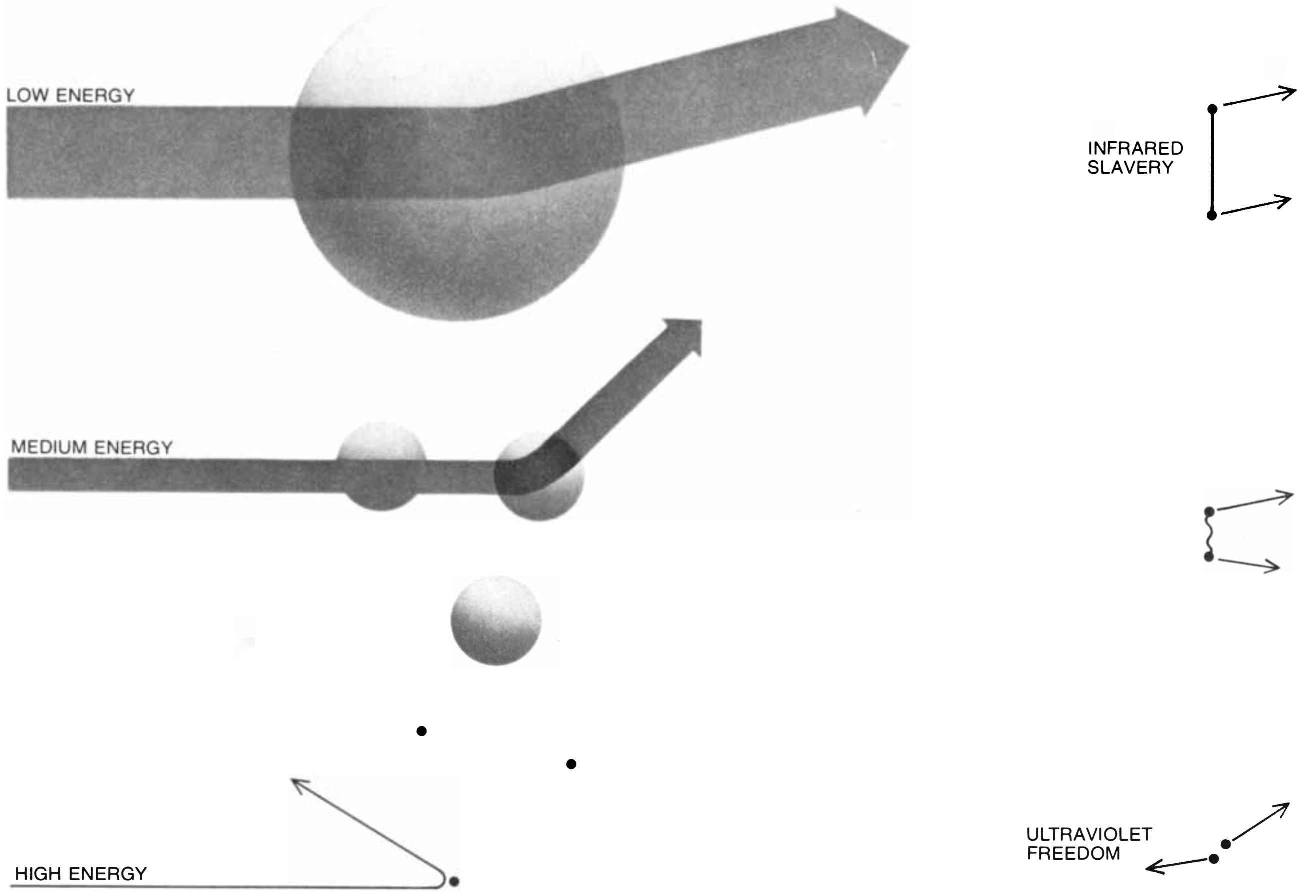
The color theory of hadron construction leads naturally to at least a partial confinement of the quarks. An atom is stablest when it is electrically neutral, that is, when it has attracted just enough electrons to balance the positive charge of the nucleus. Any attempt to add an extra electron or to remove one of those already bound is resisted. In the same way a system of quarks is stablest when all three colors, or a color and an anticolor, are present; then the hadron is neutral with respect to the two kinds of color charge. This result is hardly surprising: the color quantum numbers were introduced precisely in order to achieve an equal representation of the colors in baryons. It follows that since an isolated quark is necessarily a colored particle, it is an energetically unfavorable configuration. Free quarks will tend to associate to form colorless hadrons, just as free electrons and ionized atoms will tend to recombine. This aspect of the quark colors does not exclude the possibility of there being free quarks, but it does strongly inhibit their formation. It requires that a free quark or any other colored state be less stable, or more massive, than colorless states.

The quark model has changed significantly and grown far more elaborate since it was proposed in 1963. There is every reason to believe it will go on evolving, and it is entirely possible the present perceived need to explain the confinement of quarks will be altered by subsequent events—including, perhaps, the discovery of a free quark. The fact remains that experimental searches for quarks, guided by reasonable conjectures about their properties, have failed to reveal their presence. The consistently negative results demand explanation. One approach is to postulate a mechanism that permanently confines the quarks to the interior of a hadron, so that free quarks are not merely discouraged but are absolutely prohibited. Several theories can provide such a mechanism, and some of them exhibit exceptional ingenuity.

One of these ideas grows directly out of the underlying gauge theory of the interactions between colored quarks. Once again the principle can be effectively illustrated by considering first the analogous phenomena observed in electromagnetic interactions of matter.

The inverse-square relation of Coulomb's law has been verified with great precision at large distances, but it is not valid when the force between charged particles, such as electrons, is measured at extremely short range. The discrepancy is caused by the spatial distribution of the electron's charge. At the core of the electron there is a negative charge, called the bare charge, of very large magnitude; indeed, it may well be infinite. This charge induces in the vacuum surrounding it a halo of positive charge, which almost cancels the bare charge. The effective charge of the electron, when measured from a distance, is simply the difference between these two charges. A test particle able to approach the electron at close range will penetrate the shielding of positive charge and will begin to perceive the large bare charge.

Electromagnetism, it will be remembered, is an Abelian gauge theory, whereas the colored-quark theory of the strong force is a non-Abelian one. In this context the distinction is a crucial one, a fact that has been demonstrated by H.



INFRARED SLAVERY, one proposed explanation of quark confinement, is a concept derived directly from the field theory that describes interactions of colored quarks and gluons. The theory holds that quarks at large distances (about the size of a hadron, 10^{-13} centimeter) are bound tightly together and move in concert. The long-distance behavior of the quarks is examined by low-energy probes of the hadron, and indeed at these energies the hadron appears to be a cohesive, unified body. When the quarks are close together, on the other hand, they are only weakly bound and can move independently. The forces between quarks at this range are investigated by high-energy probes, and such experiments have observed centers of mass in the hadron that seem to move freely. The names infrared slavery and ultraviolet freedom were applied to these phenomena through analogy with the relative energies of infrared and ultraviolet radiation.

David Politzer of Harvard and David Gross and Frank Wilczek of Princeton University. In the non-Abelian theory the bare charge does not induce a shielding charge but an "antishielding" one. Thus a quark with a color charge induces around it additional charges of the same polarity. As a result the color charge of the quark is smallest at close range; as a particle recedes from the quark the charge gets larger. The corresponding force law is dramatically different from Coulomb's law: as the distance separating two color-charged particles increases, the force between them could remain constant or could even increase.

A test particle colliding with a hadron at high energy inspects the behavior of the constituent quarks over very small distances and during a very brief interval. This fact is established mathematically by the uncertainty principle, which relates the time and distance in which a measurement is performed to the energy and momentum of the test particle. It can be understood intuitively by remembering that a high-energy particle moves at nearly the speed of light and that it "sees" the quarks for only a brief moment, during which they can move only a short distance. The non-Abelian gauge theory predicts that such a high-energy probe will reveal the quarks to be essentially free particles, moving independently of one another, since at small distances the color charge declines and the quarks are only loosely bound together.

A low-energy investigation of a hadron, on the other hand, should see quarks that are rigidly tied together and therefore move as a unit. At these comparatively low energies the quarks are being observed during a more extended period, and they can interact over greater distances. Hence the more powerful long-range effects of the color gauge fields grip the quarks and bind them to one another.

Since the theory is a non-Abelian one, the gluons are subject to the same constraints as the quarks, and they are confined just as efficiently. The gluons, or the fields they represent, generate fields of their own that have the same character as the color fields of the quarks. The resulting behavior of the gluons contrasts sharply with that of photons, the quanta of the gauge fields in the Abelian theory of electromagnetism. Photons do not themselves give rise to an electromagnetic field, and they escape from such a field without hindrance.

These two opposing aspects of the color gauge theory have been given the picturesque names infrared slavery and ultraviolet freedom. The terms do not refer to those particular regions of the electromagnetic spectrum but are simply intended to suggest low-energy and high-energy phenomena respectively. Ultraviolet freedom is also known as asymptotic freedom, because the state of completely independent movement is approached asymptotically and never actually achieved. The effect may have been observed in collisions of electrons with protons, where it has been found that at very high energy the proton behaves as if it were a collection of free quarks.

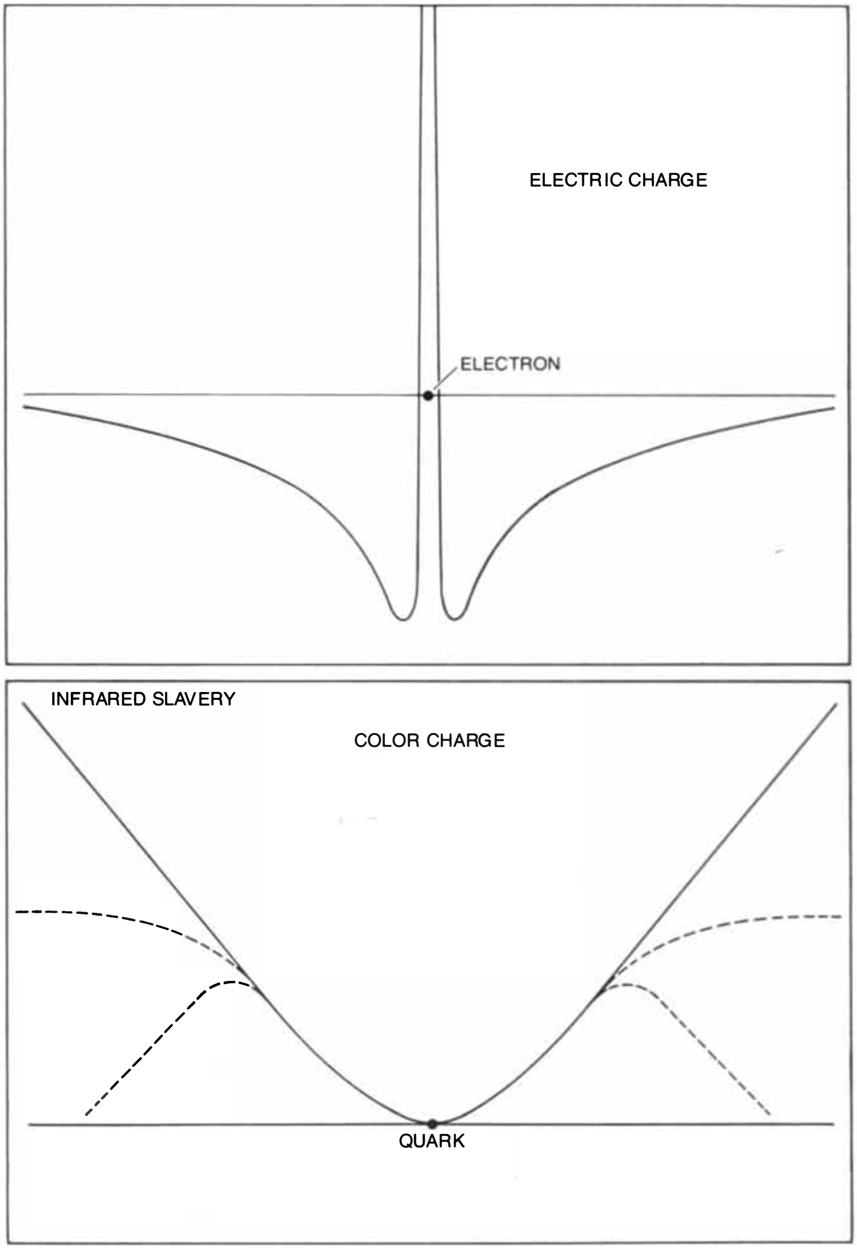
The concept of infrared slavery provides an obvious means of explaining the confinement of quarks. If the effective color charge continues to increase indefinitely with increasing distance, then so does the energy needed to pull two quarks apart. Achieving a macroscopic separation would require an enormous input of energy and would surely be a practical impossibility.

The spatial distribution of the color charge is not known, however, for macroscopic distances; indeed, nothing is known of it for any distance greater than the approximate size of a hadron: 10^{-13} centimeter. Whether or not infrared slavery can account for quark confinement depends on the details of the charge distribution. It should be pointed out, however, that the charge need not increase indefinitely to entrap the quarks permanently. It need only increase to the point where the energy required to further separate the quarks is equal to the energy needed to create a quark and an antiquark. When that energy is reached, the quark-antiquark pair can materialize. The newly created quark replaces the one extracted, and the antiquark binds to the displaced quark, forming a meson. The result is that a quark is removed from the hadron but is not set free; all we can observe is the creation of the meson.

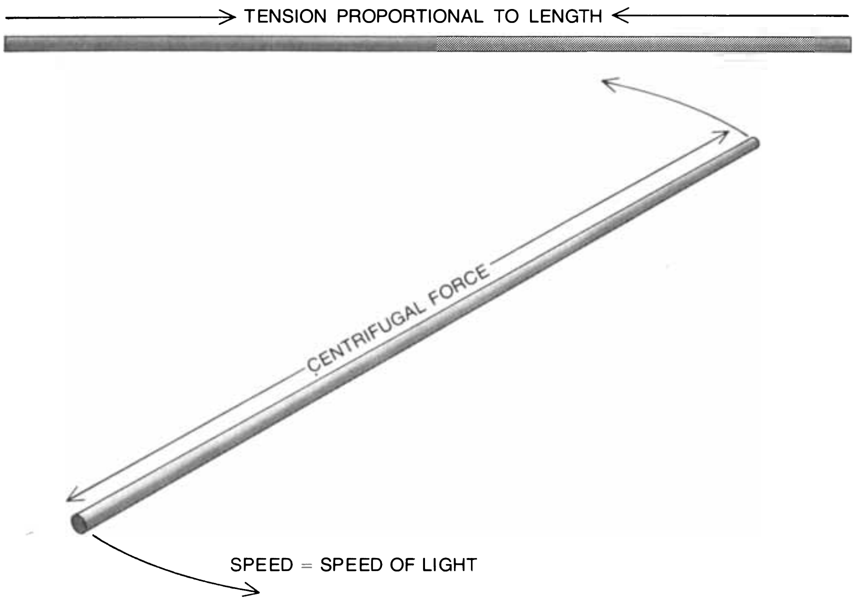
A kind of charge that increases with distance and a force that remains constant with distance seem to contradict an intuitive sense of how matter ought to behave. Quantum mechanics has contradicted intuition before, and made no apology for it, but in this case an explanation, and even a pictorial representation, of how the effects might arise may be possible. This explanation is a feature of another model of quark confinement, called the string model.

The string model grew out of mathematical formulas introduced by Gabriele Veneziano of the Weizmann Institute of Science. In the model hadrons are regarded as flexible, extensible strings in rapid rotation. The string is massless, at least in that it has no material "beads" along its length, although it does have potential and kinetic energy. The string is given a certain fixed tension as one of its intrinsic properties, so that the ends of the string tend to pull toward each other with constant force. The tension represents potential energy (just as the tension of a stretched spring does), and the magnitude of that energy is exactly proportional to the length of the string. If the string were stationary, its intrinsic tension would cause it to collapse, but the system can be kept in equilibrium by spinning the string. As the string spins it stretches, and when its length is such that its ends move with the speed of light, the centrifugal force balances the tension. (The ends are allowed to move with the speed of light, and indeed are required to do so since they are massless.)

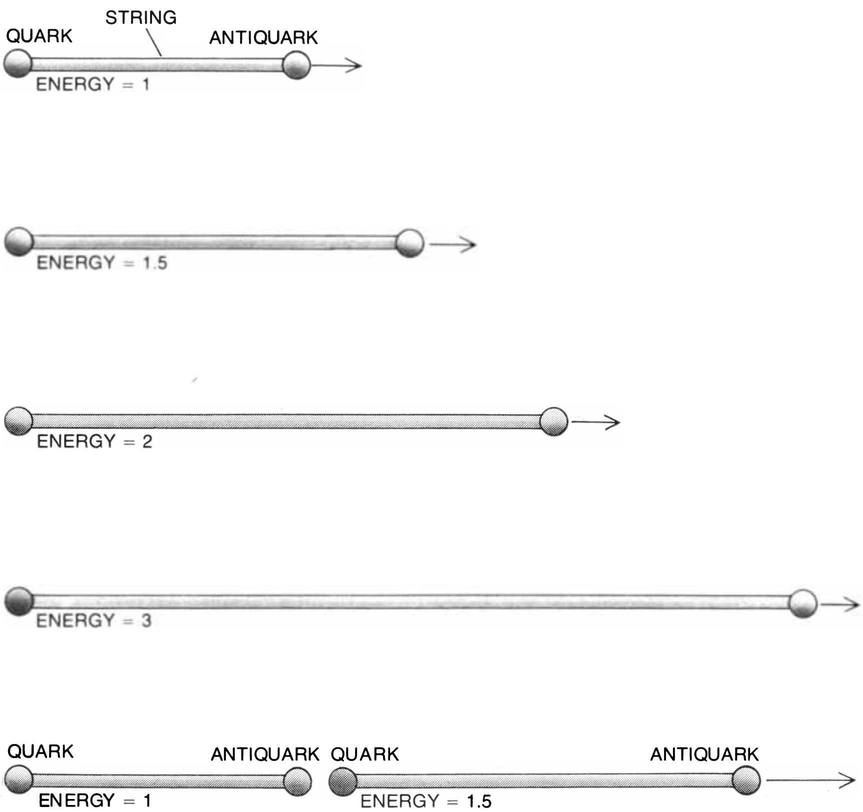
Because of the relations between length, energy and rotation that have been built into the string model, the angular momentum of the system is proportional to the square of the total energy. In this respect the model reflects an important observed property of hadrons: When the angular momentum of hadrons is plotted against the square of



DISTRIBUTION OF THE COLOR CHARGE might explain the effects of infrared slavery and ultraviolet freedom. The distribution seems to be quite different from that of the more familiar electric charge. The electron has at its core a large and possibly infinite negative charge, called the bare charge, which induces in the vacuum surrounding it a positive charge of almost equal magnitude; the effective charge of the electron observed at a distance is the difference between these charges. The bare color charge, in contrast, is thought to be very small and possibly zero, but it induces a surrounding charge of the same polarity, so that the effective charge increases, perhaps without limit, as it spreads out in space. From these charge distributions it follows that electrically charged particles obey Coulomb's law: the force between them declines as the square of the distance. Particles bearing a color charge, on the other hand, obey a very different law: the force between them remains constant, regardless of distance, and the energy with which they are bound together (or the energy that must be supplied in order to pull them apart) increases with distance. The actual distribution of the color charge has not been measured at large distances, so that several continuations of graph are possible (*broken lines*).



STRING MODEL of hadron structure leads to another possible explanation of quark confinement. The model assumes that a hadron is made of a massless, one-dimensional string that has as one of its intrinsic properties a constant tension per unit length. Because of its tension the string tends to collapse, but it can be kept in equilibrium by centrifugal force if it is made to spin so that its ends move with exactly the speed of light. These properties of the string imply that its energy is proportional to its length and that its angular momentum is proportional to the square of its energy, a relation that has been experimentally verified for the hadrons.



QUARKS WELDED TO STRINGS might be effectively confined. In order to separate the quarks it is necessary to stretch the string, but since the energy of the string is proportional to its length the energy required to pull the quarks apart increases in proportion to the separation. A macroscopic separation could be obtained only at the cost of enormous energy. In fact, isolation of a quark might not be possible at any energy, since as soon as enough energy had been supplied to create a quark and an antiquark the string might snap and these new particles appear at the ends. Thus the result is not the liberation of a quark but the creation of a meson.

their mass or energy, the result is a series of parallel lines, named Regge trajectories after the Italian physicist Tullio Regge. The relation between angular momentum and energy embodied in the string model provides a possible explanation for the observation that all the Regge trajectories are straight lines.

Quarks can be incorporated into the string model simply by attaching them to the ends of the strings. The quarks are then assumed to carry the quantum numbers of the hadron while the string carries most of the energy and momentum. Quark confinement follows as a natural consequence of the properties of the string. It is assumed that the quarks cannot be pulled off, and so the only way they can be separated is by stretching the string. Any increase in the length of the string, however, demands a proportionate increase in its energy, so that once again large separations are impossible. Nevertheless, even if the string cannot be stretched without an inordinate supply of energy, it might be snapped in two. At the breaking point a newly created quark and antiquark would be welded to the broken ends, with the result that a meson would be created. In all these interactions the string model can be seen to give results equivalent to those of the infrared-slavery hypothesis, even though the underlying description of the hadron has a quite different form.

What is the stuff of the massless spinning string? One appealing interpretation has been proposed by Holger B. Nielsen and P. Olesen of the Niels Bohr Institute in Denmark; in explaining it we shall return again to the consideration of electromagnetism. Coulomb's law describes an electromagnetic field in three-dimensional space, and if the field is represented by discrete lines of force, it is apparent that the strength of the field declines with distance because the lines spread out in space. Their density decreases as the square of the distance, giving the familiar force law. If all the lines of force could be compressed into a thin tube, the lines could not spread out and the force would remain constant, regardless of the distance.

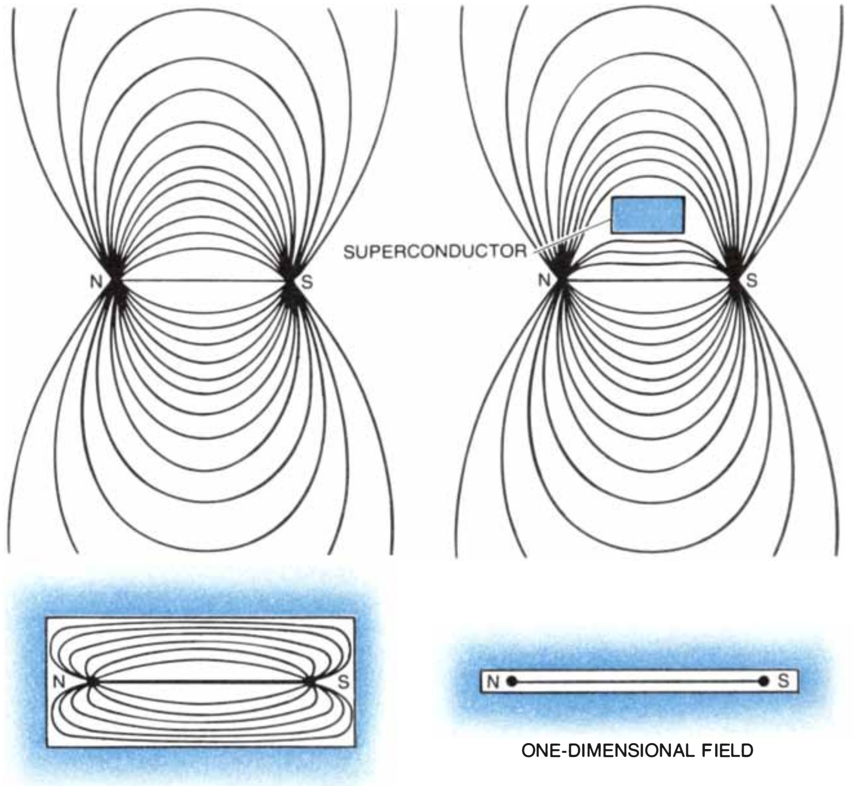
The distinctive geometry of the string suggests that it might be regarded as such a one-dimensional gauge field. The properties of the string itself—in particular the inherent tensile force and the variation of energy with length—are then as predicted by the model. Furthermore, the bizarre properties of the color gauge field are given a simple and intuitively appealing explanation. It is no longer the force itself that is peculiar; the force is a conventional one, obeying the same kind of law as electromagnetism. The peculiar properties all derive from the geometry imposed on the field.

Fields that are virtually one-dimensional can actually be created on a macroscopic scale. If a superconductor (an electrical conductor cooled to the superconducting state) is put into a magnetic field, the lines of force are expelled from the superconducting medium. If the two poles of a magnet are completely immersed in a superconductor, the lines of force are confined to a thin tube between the poles, where the superconductivity is destroyed. The tube of flux lines carries a fixed amount of magnetic energy per unit length, and the amount of magnetic flux is quantized. An exact analogy requires only that we assume that the effects of a superconducting medium on the magnetic field are duplicated in the effects of the vacuum on the color gauge field. A theory based on this comparison has been described mathematically; in it the quarks are likened to the hypothetical carriers of magnetic charge, the magnetic monopoles.

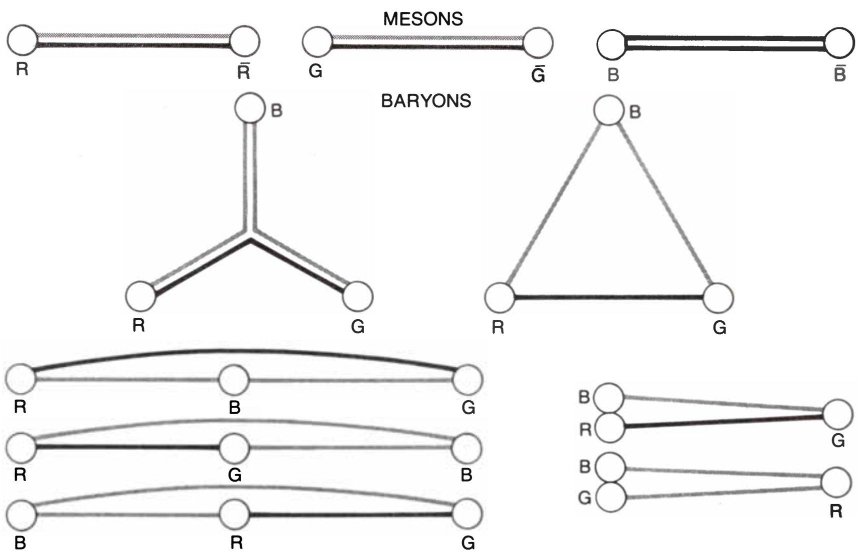
The string is a novel and amusing model of hadron structure, but attempts to make a complete and quantitative theory of it have encountered difficulties. The placement of the quarks at the ends of the string is rather arbitrary. This raises no serious problems in the case of the meson, which can be regarded as a single hank of string with a quark and an antiquark at the ends, but it is not clear what structure should be assigned to the baryon. Several configurations are possible, such as a three-pointed star, or a triangle with a quark at each vertex. The relation of mass or energy to angular momentum is very similar in baryons and mesons (that is, their Regge trajectories are nearly parallel), which implies that the internal dynamics of the two kinds of particle are also similar. This observation favors yet another possible baryon structure: a single string with a quark at one end and two quarks at the other end. In such a model, however, the colors can be assigned to the quarks in three ways, which are not equivalent to one another. Perhaps the baryon resonates between these configurations, much as the benzene ring resonates between its various possible structures.

The color-isotopic-spin and color-hypercharge quantum numbers can be accommodated in the string model by assuming that there are two kinds of string, each carrying the field associated with one of the quantum numbers. All together, though, there are eight gauge fields, represented by the eight color-anticolor combinations of the gluons. Are there then eight kinds of string also? How are we to describe the changes in the quark colors resulting from the emission or absorption of a gluon? These questions have yet to be answered satisfactorily. It may be that the simple, pictorial character of the string model is too naïve for a system in which quantum-mechanical effects are essential.

The third major attempt to account for the confinement of quarks takes a



GEOMETRY OF THE STRING might be explained through an analogy with the behavior of a magnetic field in the vicinity of a superconductor. The strength of a magnetic field declines as the square of the distance because the lines of force spread out in three-dimensional space. The flux lines are expelled by a superconductor, and if two magnetic poles are surrounded by a superconducting medium, the field is confined to a thin tube. Under these circumstances the force between the poles is constant and the energy required to pull them apart increases linearly with their separation. A string might be a similar one-dimensional field, confined not by a superconducting medium but by the vacuum. Quark confinement could then be explained even if the color charge does not increase with distance but obeys a law like that of the electric charge.



CONFIGURATION OF STRINGS linking quarks is not obvious in all cases and represents a serious impediment to the further development of the string model. It is convenient to consider two kinds of string, one associated with each of the color quantum numbers, color isotopic spin (*black*) and color hypercharge (*gray*). The binding together of a quark and an antiquark in a meson by these strings is straightforward, but baryons demand a more complex structure, for which there are several alternatives. The baryon might resonate between the various possible structures, but not all of them are satisfactory. The quarks must be able to interchange their colors without altering the mass or other properties of the hadron, but that condition is not invariably satisfied. Moreover, quark colors actually give rise to eight fields, associated with the eight gluons, rather than to two, and there is no obvious way of incorporating all into the model.

somewhat different approach but reaches a similar conclusion. This model has been proposed by Kenneth A. Johnson of the Massachusetts Institute of Technology and by others. It takes as one of its given initial conditions that the quarks are confined and from that assumption attempts to calculate known properties of the hadrons.

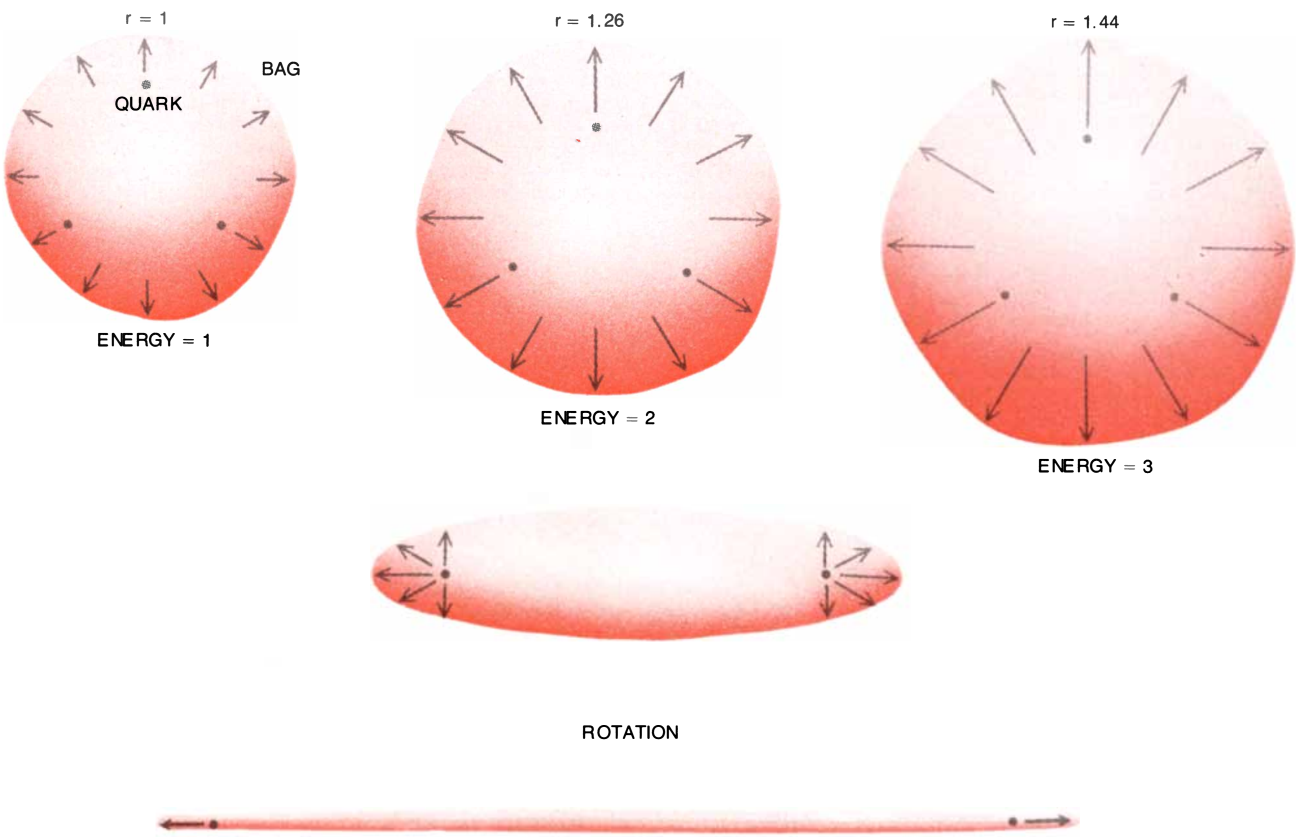
To provide containment the model employs what is perhaps the most obvious device: the quarks are trapped inside a bag, or bubble. It is a feature of the model that the quarks cannot penetrate the fabric of the bag, but by exerting pressure from inside they can inflate it. The energy of the bag itself, however, is proportional to its volume, so that large and potentially unlimited amounts of energy are required to separate the quarks. The system reaches equilibrium when the bag's tendency to shrink, in order to minimize its energy, is balanced by the pressure of the quarks inside, which move freely like the molecules of a gas. Interactions of the quarks inside the bag are governed by the standard non-Abelian gauge theory.

From the bag model it is possible to compute various properties of the proton and the neutron and of other hadrons with reasonable accuracy. The model is not very different in spirit from the Nielsen-Olesen description of the string. In one case the critical relation is between length and energy, in the other it is between volume and energy, but the effect is the same. The bag might be regarded as a string that is as thick as it is long. Conversely, if a round bag is spun fast enough, it elongates, that is, it turns into a string. Perhaps the bag will prove to be the appropriate model for discussing the ground states of hadrons, and the string will be applied to their excited, rotating states.

Each of these three models achieves its objective: it provides a mechanism for sequestering quarks inside hadrons. Each model can also account for a few properties of hadrons, but none can be considered definitive. Perhaps the comprehensive theory that will ultimately emerge will combine features of several models; for example, it would be useful to have the concept of ultraviolet freedom in the string models.

One approach to such a synthesis is being attempted by Kenneth G. Wilson of Cornell University. In Wilson's model the continuous space-time of the real world is approximated by a lattice in which the cells are the size of a hadron. Quarks can occupy any of the lattice sites and the color gluon fields propagate along straight lines (strings) linking them. Quark confinement is automatic.

Quarks are a product of theoretical reasoning. They were invented at a time when there was no direct evidence of their existence. The charm hypothesis added an extra quark explaining the properties of another large family of particles when those particles had themselves never been seen. Color, a concept of even greater abstraction, postulates three varieties of quark that may be distinct but completely indistinguishable. Now theories of quark confinement suggest that all quarks may be permanently inaccessible and invisible. The very successes of the quark model lead us back to the question of the reality of quarks. If a particle cannot be isolated or observed, even in theory, how will we ever be able to know that it exists?

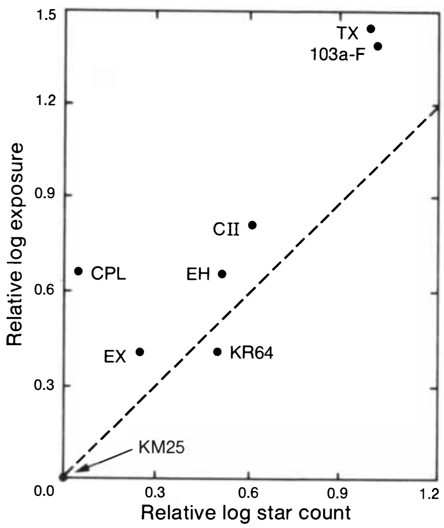


BAG MODEL of hadron structure offers a third mechanism for confining quarks. Indeed, in this model confinement is one of the initial assumptions: the quarks are assumed to be trapped inside a bag whose surface they cannot penetrate. The bag is kept inflated by the pressure of the quarks inside it, much as a balloon is inflated by the pressure of the gas inside it. The quarks can be separated only by increasing this inflation. The energy of the bag itself, however, is proportional to its volume, so that every increase in the distance between the quarks requires an additional application of energy. The bag model and the string model are closely related, and the connection between them becomes obvious when the bag is rotated rapidly: it then elongates to form an object essentially indistinguishable from a string.

How many stars are there?

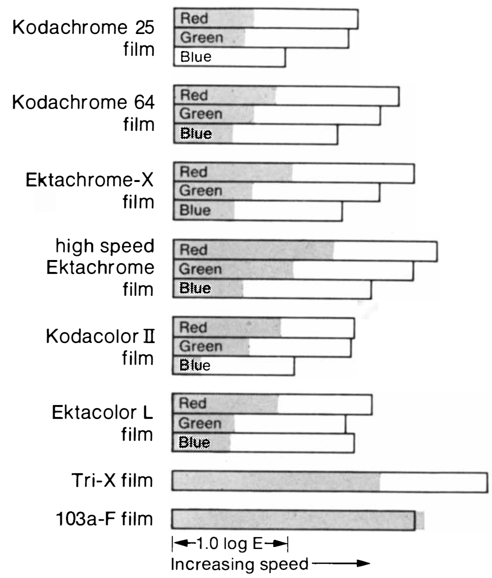
A picture is to be taken. No, several pictures. Guided exposures successively longer from "one chimpanzee, two chimpanzees, three chimpanzees" all the way to 5 minutes. In the next exciting chapter it will be found that the longer the exposure, the more stars.

The number of stars depends on the kind of film. Here is what we found when we tried it ourselves:



The origin represents one of the most available of 35 mm films, Kodachrome 25 film; *KR64,* Kodachrome 64 film; *EX,* Kodak Ektachrome-X film; *EH,* Kodak high speed Ektachrome film daylight (5033); *CII,* Kodacolor II film (5035); *CPL,* Kodak Ektacolor professional film 6102, type L; *TX,* Kodak Tri-X pan film (5063); *103a-F,* Kodak spectroscopic film, type 103a-F, acetate rem jet. For the first four of these, reversal color films, the ordinate represents threshold film speed for 5-minute exposures, specifically the logarithm of the ratio of the exposure required to create a reversed density of 3.0 on Kodachrome 25 film to that required for the same density on the plotted film; for the remaining four, negative films, the divisor is the exposure to create a density of 0.1 above minimum density. Only the blue response of the color films was used, and star counts were made from enlarged negative prints bearing a background sky density of 0.6. The color films were processed as recommended by Kodak; the two black-and-white films were developed 5 minutes in Kodak developer D-19. All points would fall on the 45° line if star count depended only on film sensitivity.

For astrophotography not requiring accommodation to the patience of youngsters and for other technical photography calling for long exposure to weak intensity—bioluminescence, for example—exposures longer than 5 minutes are often needed. Then one becomes more aware of low-intensity reciprocity failure, an effect that requires disproportionately large increases in exposure time. Emulsions vary in this respect, as shown here:



Bar length represents logarithm of speed increase for a 1-second exposure, as compared with the blue-light speed of Kodachrome 25 film for a 1000-second exposure. The unshaded portion of each bar represents speed gain when the energy is delivered over one second of time, as compared with 1000 seconds. Speed measurements of the color reversal films are on the basis of exposure required to yield an absolute density of 2.0 in the processed film; for the negative films, exposure to give a density of 0.6 above D_{min}. Overlapping of shaded area in bottom bar indicates film requires somewhat less total energy when delivered over 1000 seconds than for one second. Typical values but not specifications.

Kodak spectroscopic film, type 103a-F, may not be as widely stocked as the others, but let those who really need it note that at 1000 seconds it is even "faster" than at one second! For guidance in obtaining it and for information on Kodak spectroscopic plates, type IIIa, which permit further improvement in low-intensity speed by baking in nitrogen or hydrogen atmosphere (they are now extending the vision of the big optical telescopes to make them in effect very much bigger than when they were built), get in touch with E. J. Hahn, Scientific and Technical Photography, Kodak, Rochester, New York 14650.

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The reign continues.
Presenting the 1977 Porsche 911S, Turbo Carrera, and the Turbo RSR.
Latest descendants of an automotive engineering dynasty that began in 1948, these three automobiles represent an ongoing concept without parallel in the last half of this century.
Concept: Test, race, and refine in the unflagging pursuit of perfection.
Does it work? What single automobile has better withstood the test of time, has even approached the phenomenal racing achievements of the Porsche 911? After twenty-five years of test track, race track, and drawing board evolution, Dr. Porsche's "concept" has remained intact and achieved legendary status.
As in the past, the 911S will be available in both coupe and Targa models for 1977.
Another, more recent, case in point is the Turbo Carrera.
Newest to the Porsche stable, the Turbo is yet another engineering coup for the gentlemen in Stuttgart.


77
VEN COMES CLOSE.
Based on the 911 series, this car is the only automobile available to the American driver with a turbocharger as standard equipment.
Developing 234 HP at 5500 RPM, the Turbo will attain 60 MPH in less than 6 seconds. This makes it the fastest production Porsche ever to leave the Stuttgart factory. The rich leather interior and sumptuous appointments make it the most luxurious as well.
The rather fierce (485 HP) relative of these two automobiles is the Turbo RSR. Successor to the hugely successful Carrera RSR, Porsche's latest challenger continues to be the car to beat in Trans Am racing.
The 911S, the Turbo Carrera, the Turbo RSR.
That's what one manufacturer is doing in 1977.
And, while we always try to keep an eye on the competition, it seems we just never have time for a glance at the rear view mirror.

SCIENCE AND THE CITIZEN

The Support of Science

The emphasis on austerity and restraint in the growth of Government spending, reiterated in varying degrees by all sides in this year's Presidential and Congressional election campaigns, has had a complex and uneven effect on the portion of the Federal budget allocated for the support of science and technology in the current (1977) fiscal year. In a special message to Congress in March, President Ford stressed the commitment of his Administration to a number of positive features in the requested budget for research and development for the fiscal year 1977: an increase of between 10 and 11 percent in overall Federal spending on research and development (for a total of $24.7 billion); a 37 percent increase for energy-related research and development; a 13 percent increase for defense-related research and development; an 11 percent increase for basic research (including a 20 percent rise for the National Science Foundation); an overall increase of 10 percent for "civilian" research and development, and a 33 percent increase for new research-and-development facilities.

The Administration's proposed research-and-development budget has since then run the gantlet of Congressional review. Congress cut some research-and-development funds and increased others, with the net effect being that the total is virtually unchanged. Exact figures are not yet available, but total Federal funding for research and development in the fiscal year 1977 is now expected to be very close to the $24.7 billion recommended by the President. What trends in the Government's support of research and development do the current figures reveal?

In an effort to clarify the Federal budgetary process for the benefit of the scientific and technological community, with particular reference to the funds available for research and development, the Committee on Science and Public Policy of the American Association for the Advancement of Science earlier this year commissioned a special report on the research-and-development portion of the fiscal year 1977 budget as submitted by the President to Congress. The report, written by Willis H. Shapley, a former official of the Bureau of the Budget and, until his retirement last year, Associate Deputy Administrator of the National Aeronautics and Space Administration, was completed in April, but many of its findings continue to apply to the research-and-development budget as it stands at this stage.

According to the AAAS-sponsored report, the Administration's original budget figures for support of research and development in the fiscal year 1976, which serve as a base line for computing the percentage changes represented by the new budget figures, must first be updated by adding $298 million to take into account the overriding by Congress of the President's January veto of the fiscal year 1976 appropriation bill for the Department of Health, Education, and Welfare. On this adjusted basis the overall increase for research and development in the President's original budget for the fiscal year 1977 came to $2.135 billion, or 9.5 percent.

Taking a closer look at the trends in Federal support of research and development represented by the original fiscal year 1977 budget figures, the report found, for example, that the impressive 33.7 percent increase in funds provided for research-and-development facilities primarily reflected three factors: a large increase in projected expenditures by the Department of Defense to fund the new Air Force aircraft-engine test complex, a big jump in the Energy Research and Development Administration's budget for energy-related research-and-demonstration facilities and higher funding of NASA's space-shuttle and aeronautical-research facilities. The overall increase in research-and-development funding classified as "conduct of R&D," the report estimated, was closer to 8.5 percent.

In analyzing funding trends for "conduct of R&D," Shapley pointed out, "one must recognize that continuing inflation will have an impact on the amount of work that can be accomplished with the dollar amounts in the FY 1977 budget." Under the economic assumptions projected in the President's budget, therefore, Shapley estimated the general impact of inflation from the fiscal year 1976 to the fiscal year 1977 at 7.3 percent (including 1.5 percent for the "transition quarter": the period from July 1, 1976, through September 30, 1976, created by the recent shift in the fiscal year from July 1 through June 30 to October 1 through September 30). Accordingly in his analysis he assumed that "any R&D area increasing more than 8 percent is receiving a 'real' increase, and any area with less than a 6 percent increase is getting a 'real' cut; an increase between 6 percent and 8 percent can be taken as 'level.'"

On this basis Shapley's report showed that only three of the major research-and-development agencies would receive "real" increases in the fiscal year 1977 budget: the Department of Defense, ERDA and NSF. Two "medium-sized" research-and-development agencies (the Nuclear Regulatory Commission and the Department of Housing and Urban Development) and several of the agencies with small amounts of research-and-development funding also showed "real" increases according to his criterion, but he regarded the significance of percentage changes in these amounts as "dubious." On the other hand, according to Shapley, seven of the major research-and-development agencies showed "real" reductions, ranging from 2.3 percent to 27.3 percent; the seven agencies with less "real" money to spend in the proposed fiscal year 1977 budget are NASA, HEW, the Department of Agriculture, the Department of Transportation, the Department of the Interior, the Environmental Protection Agency and the Department of Commerce.

Thus, the AAAS report concluded, "even though the total for conduct of R&D shows a small 'real' increase of 1.2 percent, the average effect of the FY 1977 budget on all agencies other than Defense, ERDA, and NSF is a reduction of 0.7 percent in current dollars, and a 'real' reduction of 8.0 percent. From this analysis, it seems clear that the good news for R&D in the FY 1977 budget is limited to Defense, ERDA, NSF and some of the small R&D agencies. For the others, the budget clearly lives up to its primary billing for austerity and restraint."

In acting on the President's budget Congress cut back the proposed boosts in research-and-development funds for the Department of Defense (by about $540 million) and for the National Science Foundation (by more than $20 million), but it still allowed both of these agencies substantial "real" increases over their fiscal year 1976 budgets. These cuts and other, smaller ones were largely offset, however, by increases of more than $100 million for ERDA and more than $370 million for HEW. The changes, Shapley noted recently, "will have a significant impact, but they will not materially affect the overall pattern except to move HEW from the 'loser's' column to join Defense, ERDA and NSF as the agencies receiving substantial 'real' increases in FY 1977."

With respect to the unexpectedly large 11 percent increase in the funds provided for basic research in the President's proposed fiscal year 1977 budget, Shapley commented in his AAAS report, "there is no doubt that the Administration did something special for basic research in the FY 1977 budget. Apparently there was a specific last-minute de-

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You'll also find an electronically controlled DC motor that spins at exactly 33⅓ or 45 RPM. Regardless of fluctuations in AC line voltage or frequency. What's more, unlike high-speed, rumble-producing motors, our motor introduces so little vibration into the system that any rumble remains inaudible (−70 dB DIN B).

And it doesn't matter which Technics turntable you choose. Because they all have the extras you need. Like variable pitch controls. A built-in stroboscope. Viscous-damped cueing. Feedback-insulated legs. As well as a dust cover and integral base.

So if you want a turntable good enough for professionals, get the turntables radio stations use and discos abuse. Technics direct drive.

*Suggested retail price.

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cision to add $50 million for basic research to the previously decided NSF budget allowances. There was also a clearly conscious decision to provide for a sizable real increase in research, basic and applied, supported by the Department of Defense. Finally, a $20 million increase in Agriculture was specifically earmarked for basic science related to food production. But except in these preferred areas, the FY 1977 budget outlook for basic research is not so rosy."

Based on his "limited and superficial" review, Shapley reckoned that "the prospects for basic research in FY 1977 seem to be something like this: NSF has a real increase and will gain back much of the ground lost to inflation in the last 5 years. . . . The same appears to be true in the Department of Defense. [Congress's subsequent action reduced but did not wipe out the "real" increases for NSF and Defense.] ERDA is just holding its own in constant dollars; increases in in-house laboratory funds would mean reductions in grant and contract research. NASA faces a real reduction on a constant-dollar basis, and the decline in funding for scientific spacecraft development could have an impact on the level of purely 'scientific' effort in future years. HEW will probably come out of Congress with an increased budget again; whether the veto cycle will recur and what its outcome will be is anyone's guess. [Shapley's April assumptions here have since been largely borne out: Congress increased the HEW budget again; President Ford vetoed it in September, and Congress promptly voted to override his veto.] Inflation could rob Agriculture of most of its increase, but within the total available a significant redirection of effort toward the underlying scientific disciplines will presumably occur. The prospects for 'other agencies' are not known, but in such a tight budget they are not likely to be very bright."

The Shapley report was originally commissioned by the AAAS in part as a "trial run" to judge the feasibility and the desirability of an annual AAAS-sponsored report on the Federal budget. In commending Shapley for performing "what amounts to a tour de force in describing and illuminating the Federal Government's budgeting processes as they produce R&D funding outcomes," William D. Carey, executive officer of the AAAS, pointed to the dominant role played by the Federal Government in determining "the thrust and priorities of scientific research-and-development effort in the U.S." Taking this dependency relationship at face value, he said, "it seems important that scientists and engineers brush up on their understanding of the Government's budgeting process as it concerns research and development." The growth in the impact of Federal funding on the conduct of science and technology in the U.S. is underscored by the fact that the Government currently provides more than half of all support for research and development and about two-thirds of the total support for basic research.

The Great Transition

Students of the human population speak of the "demographic transition" as the process whereby the population of the world may eventually reach a level at which it remains stable. In such a transition a society moves from a stage of high birth and death rates to one of low birth and death rates. Usually the decline in the birth rate follows the decline in the death rate by several generations; during the period when the rates differ the population of the society goes up. Evidence that the demographic transition is at work appears in a report, *World Population: 1975,* published by the Bureau of the Census of the U.S. Department of Commerce. The data were assembled by the International Statistical Programs Center of the bureau.

Since 1950, according to the report, "death rates have fallen faster than birth rates in the less developed regions," with the result that their average rate of growth increased from 1.8 percent per year in the period from 1950 to 1955 to 2.2 percent per year from 1970 to 1975. "In the more developed countries, on the other hand, a substantial decline occurred in the average annual growth rate . . . thus largely offsetting the increase in the growth rate of the less developed countries." (The decline was from 1.3 percent per year in 1950–1955 to .8 percent per year in 1970–1975.) During the 25-year period, according to the report, the world's population rose from 2.5 billion to about four billion.

Among the major regions Latin America had the highest annual growth rate, which in the 1970–1975 period reached 2.8 percent per year. "Excluding Temperate South America (Argentina, Chile, the Falkland Islands and Uruguay), which the United Nations considers a more developed region, the population of Latin America more than doubled between 1950 and 1975, from 139 million to 283 million persons." In Africa the average growth rates are relatively low for less developed regions, but death rates are "still much higher than in other areas, and their eventual decline portends an even further increase in the African growth rate." In Asia "it is not so much the growth rate that commands attention, but the sheer size of the population." In 1950 about half of the world's population lived in Asia; by 1975 the proportion was 57 percent. Europe, including the U.S.S.R., had the lowest growth rate (1.1 percent in 1950–1955 and .7 percent in 1970–1975), and in North America the rate "has steadily declined since 1950," reaching .9 percent in 1970–1975.

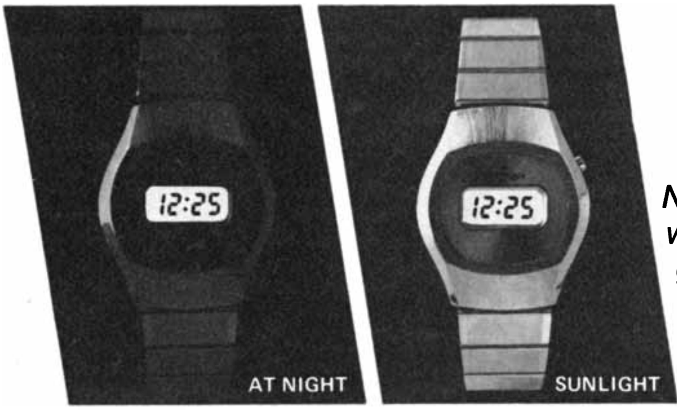
In two major countries the level of population is already stable or close to it: Austria has a growth rate of zero and Belgium one of .3 percent. The U.S. has an annual birth rate of 15 per 1,000 population, a death rate of nine per 1,000 and a growth rate of .8 percent per year. The two Germanies are in the unusual position of having birth rates lower than death rates: respectively 11 and 14 per 1,000 in East Germany and 10 and 12 per 1,000 in West Germany.

The survey gives data for every country with a population of at least 2,000, although the information is not complete in every case. Among other facts that emerge is that Sweden is the nation with the longest life expectancy (75 years) at birth, Guinea the nation with the shortest (27 years). The median age of the women who became mothers during a given year was 23 in the German Democratic Republic (East Germany) and 30 in Pakistan and Ireland.

Interferon v. Hepatitis

Ever since the discovery in 1957 of interferon, a protein that is induced in animal cells by a virus and subsequently protects other cells against that virus and different ones, the obvious hope has been that the substance would prove to be as effective clinically against viruses as antibiotics are against bacteria. The hope has been difficult to fulfill. Interferon has turned out to be a complex protein that appears in many different forms and has a confusing multiplicity of effects. Its production by cells can be induced by treating either the separated cells or the whole animal, including man, with a variety of agents in addition to viruses. Attempts to administer an inducing agent to human patients and thus make the body manufacture effective amounts of endogenous interferon have so far not been successful, however. Exogenous interferon can be prepared most successfully by stimulating human white blood cells with Sendai virus. Such interferon is very expensive, however, so that although large doses have been shown to have some effect on cold viruses, interferon is not a practical agent for prophylaxis against the common cold. In recent trials interferon has therefore been tested against more serious virus diseases.

Now a team of physicians at the Stanford University School of Medicine has reported that treatment with interferon seems to have an effect on a serious chronic infection associated with acute serum hepatitis, or hepatitis B. About 10 percent of the patients hospitalized in the U.S. with hepatitis B become chronically infected; they can suffer repeated episodes of active hepatitis, with associated liver damage, and they act as carriers who can infect other people with



Laser Beam Digital Watch

Never press another button, day or night, with America's first digital watch that glows in the dark.

Announcing Sensor's new Laser 220—the first really new innovation in digital watch technology.

It's ingenious, it's simple and it makes every other digital watch obsolete. Scientists have perfected a digital watch with a self-contained automatic light source—a major scientific breakthrough.

SELF-CONTAINED LIGHT SOURCE

The Laser 220 uses laser beams and advanced display technology in its manufacture. A glass ampoule charged with tritium and phosphor is hermetically sealed by a laser beam. The ampoule is then placed behind the new Sensor CDR (crystal diffusion reflection) display.

The high-contrast CDR display shows the time constantly—in sunlight or normal room light. But, when the room lights dim, the self-contained tritium light source automatically compensates for the absence of light, glows brightly, and illuminates the display.

No matter when you wear your watch—day or night—just a glance will give you the correct time. There's no button to press, no special viewing angle required, and most important, you don't need two hands to read the time.

Replace the battery yourself by just opening the battery compartment with a penny. Free batteries are provided whenever you need them during the five-year warranty.

A WORRY-FREE WATCH

Solid-state watches pose their own problems. They're fragile, they must be pampered, and they require frequent service. Not the Laser 220. Here are just five common solid-state watch problems you can forget about with this advanced space-age timepiece:

1. Forget about batteries The Laser 220 is powered by a single EverReady battery that will actually last years without replacement—even if you keep the 220 in complete darkness. In fact, JS&A will supply you with the few batteries you need, free of charge, during the next five years. To change the battery, you simply unscrew the battery compartment at the back with a penny and replace the battery yourself.

2. Forget about water Take a shower or go swimming. The Laser 220 is so water-resistant that it withstands depths of up to 100 feet.

3. Forget about shocks A three-foot drop onto a solid hardwood floor or a sudden jar. Sensor's solid case construction, dual-strata crystal, and cushioned quartz timing circuit make it one of the most rugged solid-state quartz watches ever produced.

4. Forget about service The Laser 220 has an unprecedented five-year parts and labor warranty. Each watch goes through weeks of aging, testing and quality control before assembly and final inspection. Service should never be required. Even the laser-sealed light source should last more than 25 years with normal use. But if it should require service anytime during the five year warranty period, we will pick up your Sensor, at your door, and send you a loaner watch while yours is repaired—all at our expense.

5. Forget about changing technology The Sensor Laser 220 is so far ahead of every other watch in durability and technology that the watch you buy today, will still be years ahead of all others.

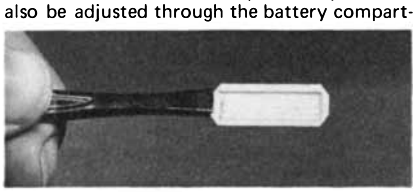
THE ULTIMATE ACHIEVEMENT

Other manufacturers have devised unique ways to produce a watch you can read at a glance. The new $300 LED Pulsar requires a snap of the wrist to turn on the display, but the Pulsar cannot be read in sunlight. The new $400 Longine's Gemini combines both an LED and liquid crystal display. (Press a button at night for the LED display, and view it easily in sunlight with the liquid crystal display.) But you must still press a button to read the time. All these applications of existing technology still fail to produce the ultimate digital watch: one you can read under all light conditions without using two hands. Until the introduction of the Sensor.

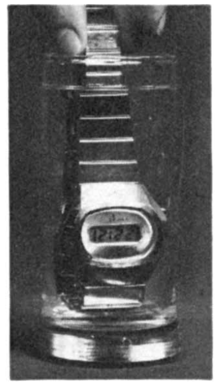
PLENTY OF ADVANCED FUNCTIONS

Sensor's five time functions give you everything you really need in a solid-state watch. Your watch displays the hours and minutes constantly, with no button to press. But depress the function button and the month and the date appear. Depress the button again and the seconds appear. To quickly set the time, insert a ball-point pen into the recessed time-control switch on the side. It's just that easy.

Sensor's accuracy is unparalleled. All solid-state digitals use a quartz crystal. So does the Sensor. But crystals change frequency from aging and shock. And to reset them, the watch case must be opened and an airtight seal broken which may affect the performance. In the Sensor, the crystal is first aged before it is installed, and secondly, it is actually cushioned in the case to absorb tremendous shock. The quartz crystal can also be adjusted through the battery compartment without opening the case. In short, your watch should be accurate to within 5 seconds per month and maintain that accuracy for years without adjustment and without ever opening the watch case.



The new exclusive laser-sealed tritium and phosphor light source is a thin solid-state tube that automatically illuminates the display when the lights dim.



Would you do this with your solid-state watch? Of course not. Most solid-state watches require care and pampering but not the Sensor. You can dunk it, drop it and abuse it without fear during its unprecedented five-year parts and labor warranty.

STANDING BEHIND A PRODUCT

JS&A is America's largest single source of digital watches and other space-age products. We have selected the Sensor Laser 220 as the most advanced American-made, solid-state timepiece ever produced. And we put our company and its full resources behind that selection. JS&A will warranty the Sensor (even the batteries) for five full years. We'll even send you a loaner watch to use while your watch is being repaired should it ever require repair. And Sensor's advanced technology guarantees that your digital watch will be years ahead of any other watch at any price.

Wear the Laser 220 for one full month. **If you are not convinced that it is the most rugged, precise, dependable and the finest quality solid-state digital watch in the world, return it for a prompt and courteous refund. We're just that proud of it.**

To order your Sensor, credit card buyers may simply call our toll-free number below or mail us a check in the amount indicated below plus $2.50 for postage, insurance and handling. (Illinois residents add 5% sales tax.) We urge you, however, to act promptly and reserve your Laser 220 today.

Stainless steel w/leather strap $129.95
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hepatitis either through blood transfusion or in other ways that are not yet well defined. Chronic infection is characterized by the continued presence in the blood of a hepatitis-B surface antigen and sometimes by markers indicating the presence of Dane particles, which are thought to be the hepatitis virus particles themselves. The markers include a particle-core antigen, a specific form of the enzyme DNA polymerase and a specific circular double-strand DNA.

The Stanford workers, who reported their results in *The New England Journal of Medicine,* are Harry B. Greenberg, Richard B. Pollard, Larry L. Lutwick, Peter B. Gregory, William S. Robinson and Thomas C. Merigan. They treated four chronic-hepatitis patients, three of whom had elevated Dane-particle polymerase levels. Brief courses of treatment with large doses of human-blood-cell interferon brought about transient decreases in the blood levels of Dane-particle polymerase and other markers; sustained treatment with rather small doses reduced the blood levels significantly, and the low levels persisted for some weeks after treatment was terminated. The Stanford investigators conclude that interferon "appears to be exerting a suppressive effect on the production of Dane particles," that is, it seems to be interfering with the multiplication of the putative virus particles. They hope now to do a clinical trial that will evaluate interferon's effect on the liver disease caused by chronic hepatitis-B infection and show whether or not it can actually improve liver function.

Fast Clock

A decade-old method of measuring evolutionary change, based on the principle that random mutations occur at a constant rate over long periods, has failed to fulfill its early promise. The method compared mutation-derived differences that have accumulated between different animal species in the primary amino acid sequences of such blood proteins as hemoglobins, myoglobins, immunoglobulins and serum fractions. The differences were then used to establish sequences of evolutionary branching, not only between various animal species but also between species in the plant and animal kingdoms. For example, the method placed the appearance of an ancestor common to both man and bacteria at a time about three billion years ago and went on to distribute estimated branching times for various lines of mammalian descent across the 90-million-year period since the first mammals appeared during the Mesozoic era.

Last year 16 scholars in the fields of primate paleontology, anthropology and molecular biology, including Emile Zuckerkandl of the Marine Biological Laboratory at Woods Hole, met at a Wenner-Gren Foundation symposium some 13 years after Zuckerkandl at a previous symposium had coined the term "molecular anthropology." They compared the branching times for a number of related primates, as suggested by the protein clock, with the times suggested by the fossil record. The most immediate discrepancy involved the evolutionary distance between man and the chimpanzee. Protein-clock estimates pinpoint the separation of these two hominoid genera at a time no longer ago than three to four million years. The fossil record, supported by such indicators of absolute age as radioactive-isotope ratios, indicates that several proto-humans had already evolved by then. The paleontologists at the symposium, Elwyn L. Simons of Yale University and Alan Walker of Harvard University, noted that the ancestral separation of man and chimpanzee almost certainly antedates the appearance of an anatomically closer relative of man, *Ramapithecus,* in the fossil record some 15 million years ago.

A second discrepancy concerned an even earlier branching, that which separates the majority of primates, the Anthropoidea, into two main divisions: the New World monkeys on the one hand and the Old World monkeys and hominoids on the other. The protein clock places this split about 35 million years ago. The fossil record places it 15 to 20 million years earlier, a position that corresponds with current estimates of when the American and Eurasian landmasses drifted apart. Still a third discrepancy appeared with respect to the division of the Old World anthropoids into two groups: the cercopithecoid monkeys and the hominoids. The protein clock suggests a split only 20 million years ago; the fossil record suggests that it may have been twice that long ago.

Eighteenth-Century Quarks

The theory that protons and neutrons are made up of pointlike entities called quarks is one of the newer ideas in physics, but it is not without antecedents. Phillip M. Rinard of Emporia Kansas State College has recently called attention to a particularly striking relation between the quark model and the ideas of the 18th-century philosopher and mathematician Roger Boscovich.

Quarks have a number of properties that set them apart from all other particles; among these distinguishing traits is the force that binds quarks together inside the usual kind of particle. Whereas all the familiar forces in nature—such as gravitation and electromagnetism—decline with increasing distance, the force between quarks may remain constant or even increase, with the result that the quarks are permanently bound (see "The Confinement of Quarks," by Yoichiro Nambu, page 48). It is this peculiar force law that is foreshadowed in the work of Boscovich.

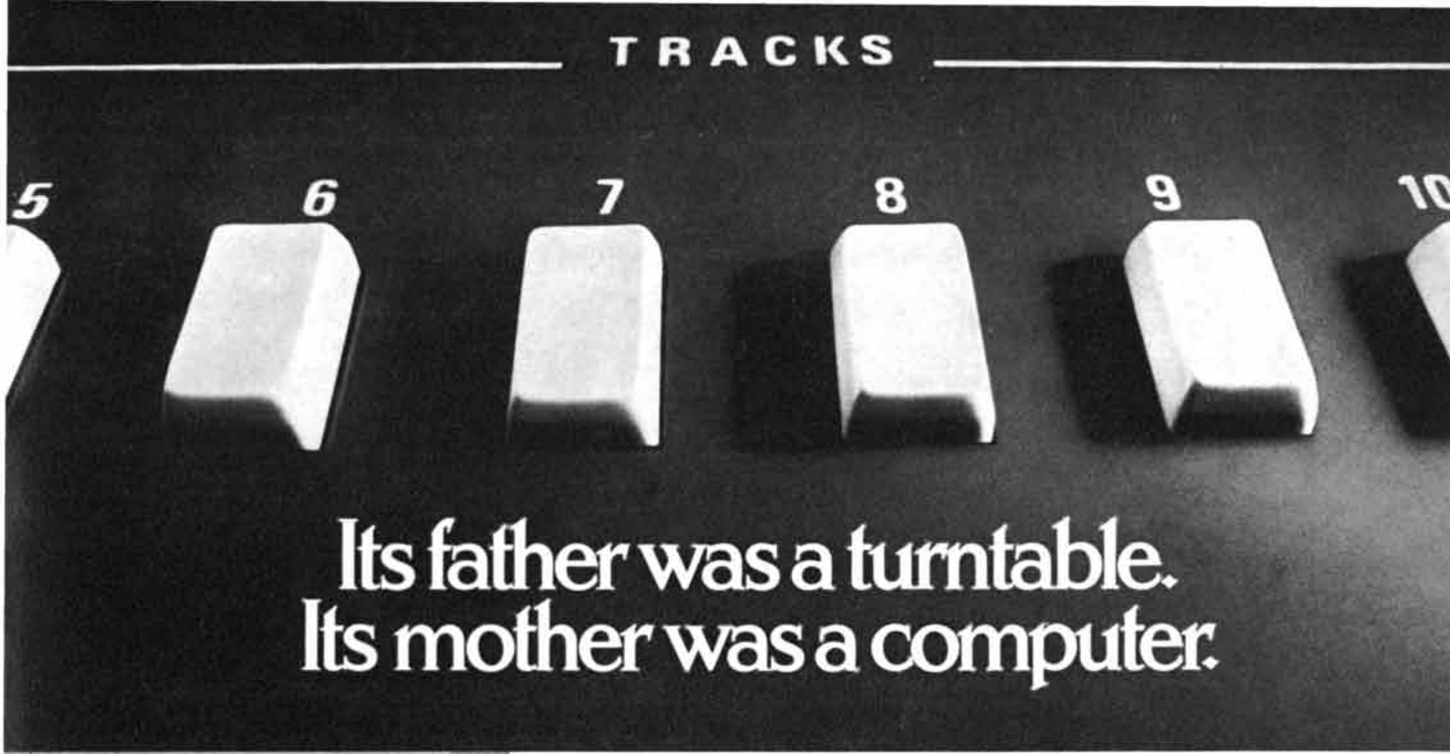
Boscovich, born in 1711 at Dubrovnik in what is now Yugoslavia, was a Jesuit scholar and professor of mathematics in Rome. The work for which he is best known today is an elegant theory, inspired by the earlier work of Newton, describing the structure of matter. Boscovich was able to explain all the forms of matter by postulating a single kind of elementary particle, a degree of simplicity not yet approached by modern physical theories. The particles were imagined to be impenetrable, infinitely small points floating in a vacuum. Moreover, all of them were considered to be identical; the varied forms of matter resulted from the relative positions and velocities of the particles.

Boscovich determined that at very small distances the force between these ultimate atoms must be repulsive, and that as the distance was reduced to zero the force must increase without limit, so that the particles could never actually touch. At large distances the force was attractive and declined as the square of the distance: it was equivalent to gravitation. At intermediate distances the force was alternately attractive and repulsive.

It has been known for some time that Boscovich's theory predicts a number of phenomena he could not have anticipated. For example, his particles can never be absolutely motionless, a constraint that applies to real atoms obeying the rules of quantum mechanics. Because the force between particles alternates between attraction and repulsion there are several points of stable equilibrium, favoring the creation of bound systems in which the particles can have certain discrete separations. The equilibrium points could be regarded as a crude approximation of the quantized orbitals, or energy levels, of electrons in an atom.

Rinard, writing in *American Journal of Physics,* points out that Boscovich's force law might also describe some of the apparent interactions of quarks. Like the electrons in atoms, quarks bind together in stable, quantized orbitals, which could be interpreted in terms of the equilibrium points intrinsic to the Boscovich theory. Furthermore, beyond each equilibrium point is a region characterized by an attractive force, so that quarks pulled apart would tend to return to their equilibrium configuration. If the attractive potential were large enough (Boscovich did not specify its magnitude), the quarks might be permanently confined.

Rinard does not suggest that Boscovich actually discovered the laws governing the motion of quarks. What is remarkable is that the two theories, formulated 200 years apart, both depend ultimately on the same concepts of simple particles and forces.



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Convection Currents in the Earth's Mantle

The steady motion of the plates that form the earth's crust is evidence for convection currents on a vast scale. Laboratory studies indicate that there should be smaller currents as well

by D. P. McKenzie and Frank Richter

Geophysicists have long conjectured that the rock of the earth's mantle, the deep plastic region below the earth's rigid crust, must be churning slowly in vast convection cells, rising in some regions, cooling and sinking in others. In the past dozen years, with the general acceptance of the concept of plate tectonics, the existence of convection has become apparent on a global scale. The crust of the earth is made up of large quasi-rigid plates that grow outward from rifts in the ocean floor where molten rock wells up and eventually plunge back into the mantle in the vicinity of deep ocean trenches. The motion of the plates from a mid-ocean ridge to a trench provides the visible half of the convection loop. The mass of the plunging plate must be conserved and the loop closed by a deep return flow of material from the trench to the ridge. Since the horizontal dimension of the loop corresponds to the dimensions of a plate, the complete loop is now often called the large-scale circulation. In the case of the Pacific plate the horizontal dimension reaches 10,000 kilometers.

Although the large-scale circulation can now be accurately described, and almost certainly represents a form of thermal convection in the earth's upper mantle, there is still no satisfactory theory explaining how the circulation is maintained for tens of millions of years. Attempts to answer the question with the help of laboratory experiments and computer simulation have yielded evidence for the possibility of convection on a smaller scale, where the convection cells would have a horizontal dimension comparable to their depth: about 700 kilometers. The experiments suggest that such cells could explain the flow of heat under old sections of oceanic plates, which is greater than one would expect, and perhaps could account for gravity anomalies in the ocean floor. Small-scale convection cells might also provide the rising jets of hot material that create oceanic chains of volcanoes such as the Hawaiian Islands. Finally, the experiments suggest that the small-scale convection cells may be aligned in long parallel cylinders under plates that are moving as fast as the Pacific plate. It has not yet been possible, however, to simulate in the laboratory the large-scale convection that is apparent in the overall motion of the plates.

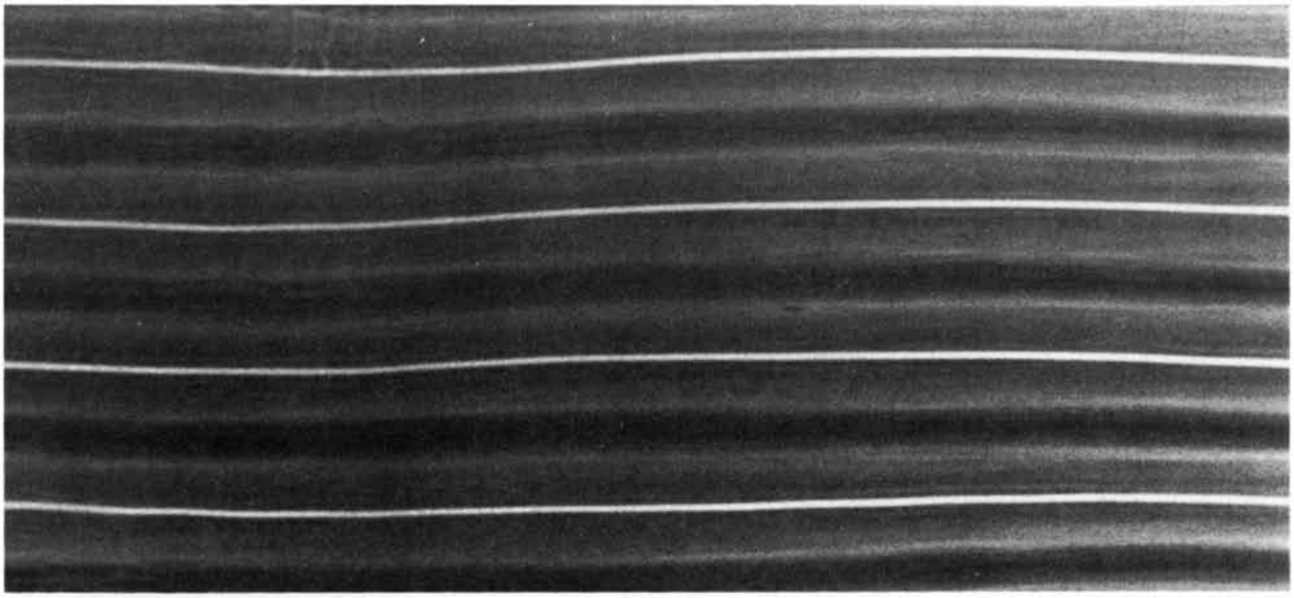
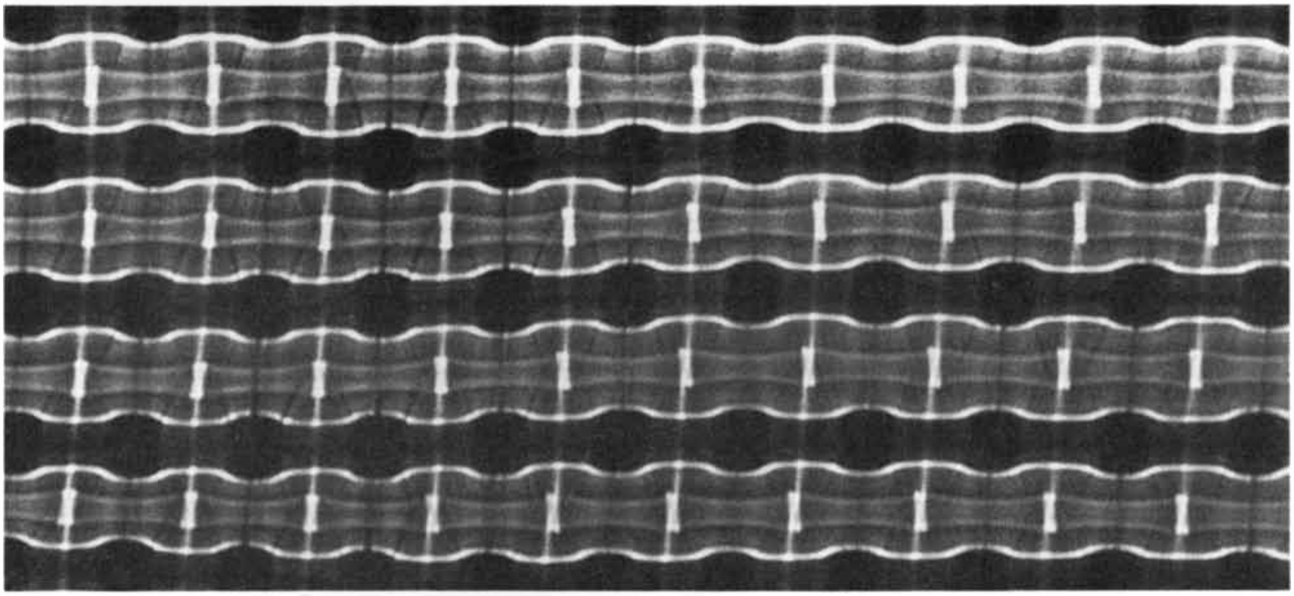
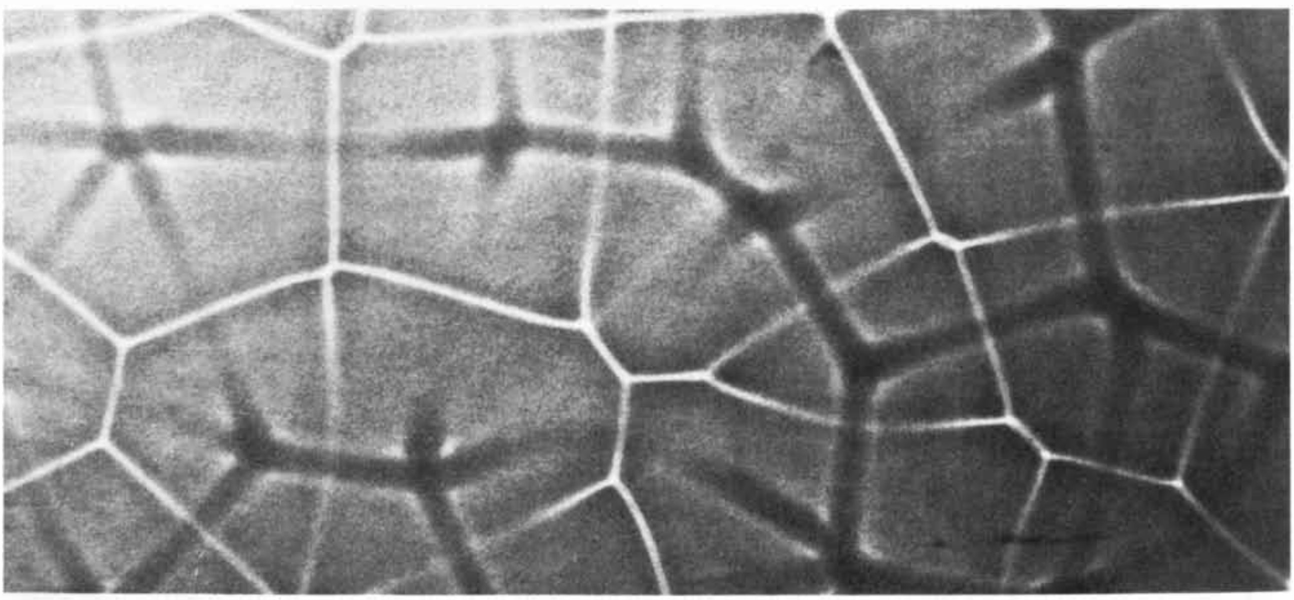
The Motions of the Plates

In any effort to understand the forces that drive the plates the most straightforward approach is to start from theoretical models of worldwide plate motions, which impose some constraints on the possible driving mechanisms. Almost all large earthquakes are triggered by plate motions, so that the energy released by earthquakes must be provided by the forces driving the plates. Many mechanisms have been proposed as a source of the energy, but few are adequate to account for it. The only mechanisms that easily provide enough energy are convective flow in the mantle and the process of differentiation by which iron present in the mantle became dissociated from other elements and sank to form the earth's core. As we shall see, thermal convection can give rise to a large variety of flow patterns; the neat hexagonal arrangement of convection cells so common in textbooks is extremely rare in nature.

Thermal convection involves the transport of heat by the coherent motion of material rather than by radiation or diffusion. In the type of convection that is of interest in plate tectonics the heat is transported upward and the flow is driven by the difference in density between the hot fluid and the cold. Even the most conservative estimates of the buoyancy forces resulting from plate motions are much larger than the forces involved in earthquakes. This argument has convinced many geophysicists, but by no means all of them, that the plate motions are maintained by some form of convection.

Geophysical observations can tell us a little about how deep the convective flow extends. No earthquake focus has yet been accurately located whose depth is greater than 700 kilometers. Furthermore, the slabs sinking under the arcs of islands where plates converge are in compression at all depths when their advancing edge extends to depths of more than 600 kilometers, whereas they are in tension at depths of less than 300 kilometers if their leading edge does not reach 300 kilometers. The simplest explanation of this behavior is that the slab meets great resistance to its motion at 600 kilometers and is unable to penetrate below 700 kilometers. The in-

SHADOW PATTERNS OF CONVECTION CELLS are seen from above in a laboratory apparatus designed to simulate conditions that may produce convection in the plastic rock of the earth's upper mantle. The patterns are made visible in the apparatus by shining light through a transparent viscous fluid from below (*see illustrations on page 80*). The rays are refracted away from hot regions and toward cold ones, giving rise to light and dark patterns. The changes in laboratory conditions responsible for the various patterns can be summarized in terms of the Rayleigh number, a dimensionless quantity that is proportional to the temperature difference across the layer of fluid and to several other parameters, including the thickness of the layer. When the Rayleigh number is less than about 1,700, there is no convection. When the Rayleigh number is between 1,700 and about 20,000, convection takes the form of two-dimensional parallel cylinders, as is shown in the top photograph on the opposite page. At Rayleigh numbers between 20,000 and 100,000 two sets of cylinders at right angles to each other are generated (*middle photograph*). This convection pattern is called bimodal flow. At still higher Rayleigh numbers the flow assumes an intricate spoke pattern in which sheets of rising hot fluid and sinking cold fluid radiate out from multiple centers (*bottom photograph*).

crease in the resistive force is probably associated with a change in the crystal structure of iron and magnesium silicates that occurs at this depth. Whatever the explanation, the behavior of sinking slabs strongly suggests that the convective circulation of which the plates are a part is confined to a region 700 kilometers deep. What happens deeper in the mantle need not concern us here (although it seems likely that convection also occurs in the lower mantle).

It is difficult to say much more about the form of the flow from geophysical observations alone. The plates are large and strong, and their rigid motions conceal the more complicated three-dimensional motions in the mantle below. It is much harder to study convection in the mantle than it is to study the circulation of the ocean or of the atmosphere. There is no drill that can bore through a plate; the deepest boreholes sample only the top 10 percent of it. And even if one could penetrate to the mantle, one would have the problem of measuring convection currents that move at velocities of only a few centimeters a year.

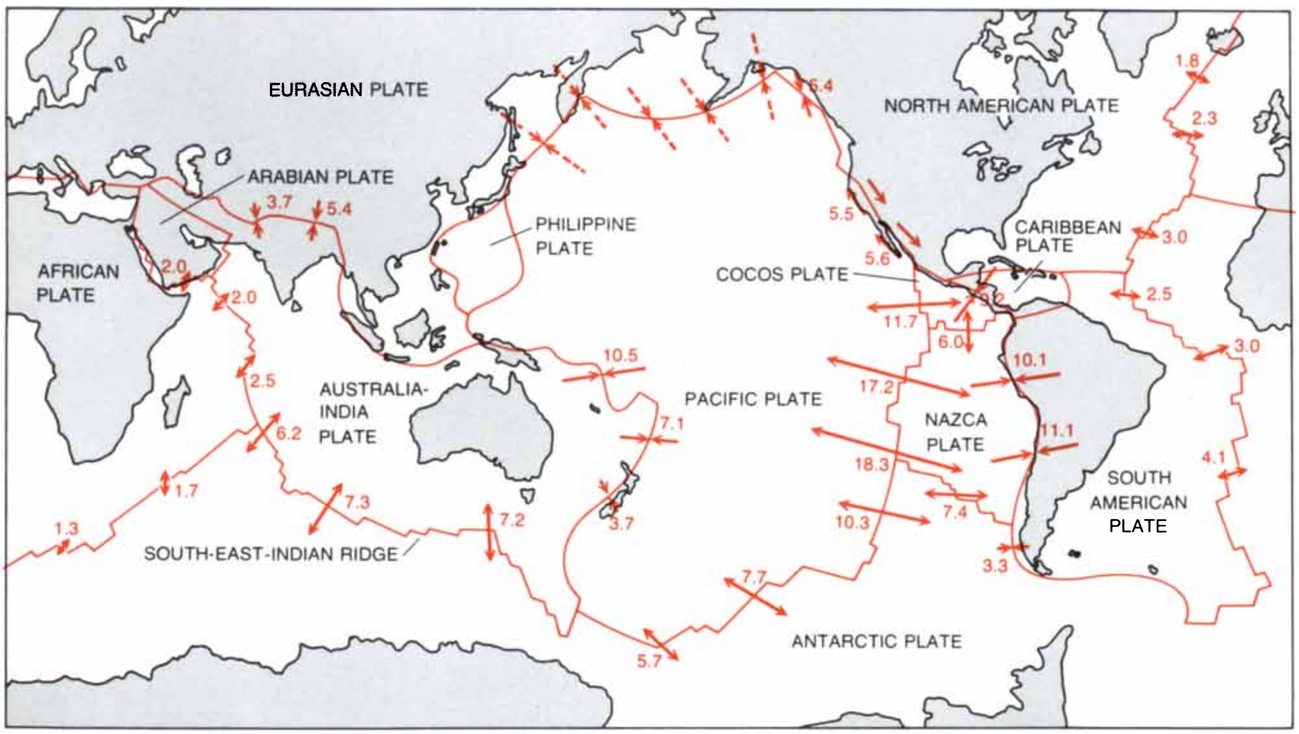
The Rayleigh and Reynolds Numbers

Fortunately mathematical physicists have been interested in convection since the 19th century, so that there is considerable understanding of how convection currents behave. Perhaps the most striking finding is how complicated the convective flow can be even in a layer of fluid uniformly heated from below. Undoubtedly convection in the earth's mantle is more complicated still.

Two of the leading contributors to the mathematical description of fluid flow, including convection, were Lord Rayleigh and Osborne Reynolds. Largely as a result of their work it is possible to describe any type of convective flow with only a few numbers, named after Rayleigh and Reynolds, that are dimensionless combinations of various physical parameters such as viscosity, thermal conductivity and the coefficient of thermal expansion. With the aid of these numbers one can simulate the convection in the earth's mantle in a layer of fluid a few inches thick. The reason is that convection depends on the combined properties of the fluid layer and not on the properties taken singly. The Rayleigh number depends in part on the ratio between the cube of the depth and the viscosity, so that one can model a system such as the upper mantle, which has a very high viscosity and a depth of hundreds of kilometers, with a fluid of moderate viscosity. One can also speed up the passage of time so that processes that could take millions of years in the earth take only a few hours in the laboratory model.

The Rayleigh number is particularly significant for modeling convection. It is proportional to the temperature difference between the top and the bottom of the fluid and to several other parameters. In a convecting fluid the Rayleigh number is in practice proportional to the ratio between the time needed to heat a layer of fluid by thermal conduction and the time needed for a particle of fluid to circulate once around the convection cell. A familiar example of a convecting fluid with a large Rayleigh number is water being heated in a saucepan but not yet boiling. The fluid inside an egg placed in the pan represents a system with a small Rayleigh number because the contents of the egg are much more viscous than water. (As a result the heat that cooks the egg is distributed by conduction rather than by convection.)

The Reynolds number is concerned not with heat but with momentum. It measures the ratio between the forces accelerating the fluid and the viscous forces resisting its motion. When the Reynolds number is small, the inertia of the fluid is not important and the flow is fairly simple. If the number is large, however, eddies are likely to form and the flow can become turbulent and extremely complex. Examples of flow with a high Reynolds number are water gushing from a faucet or a mountain stream tumbling over rocks. Atmo-



EVIDENCE FOR CONVECTION IN THE MANTLE is supplied by the motions of the dozen or so plates into which the earth's crust is divided. Material is added to the plates by upwelling of molten rock along rifts in the ocean floor that mark the center of a ridge extending continuously for some 40,000 miles through the Atlantic, Indian and Pacific oceans. The plates plunge back into the mantle at subduction zones that coincide with oceanic trenches. The lines with arrowheads pointing outward show where plates are moving apart at ridges; numbers indicate the relative velocity in centimeters per year. The Australia-India, Pacific and Nazca plates are moving the most rapidly. Lines with opposed arrowheads show where plates are moving toward each other, usually at trenches. The Himalayas are a major exception. Plates can also slide past each other along transform faults such as San Andreas fault on west coast of North America.

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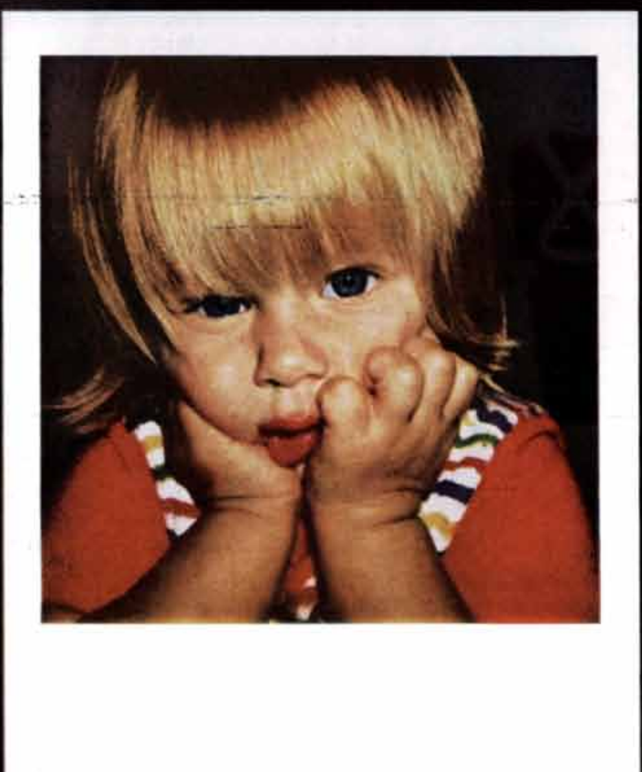

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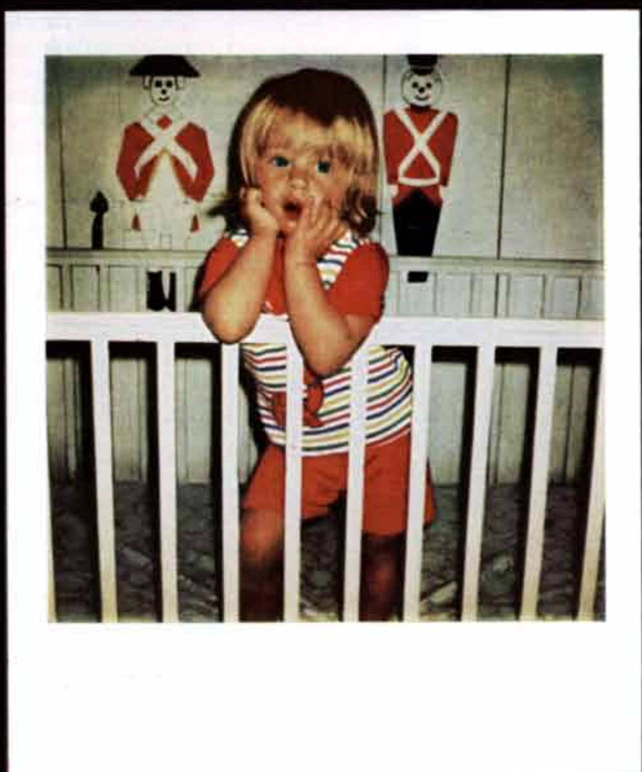

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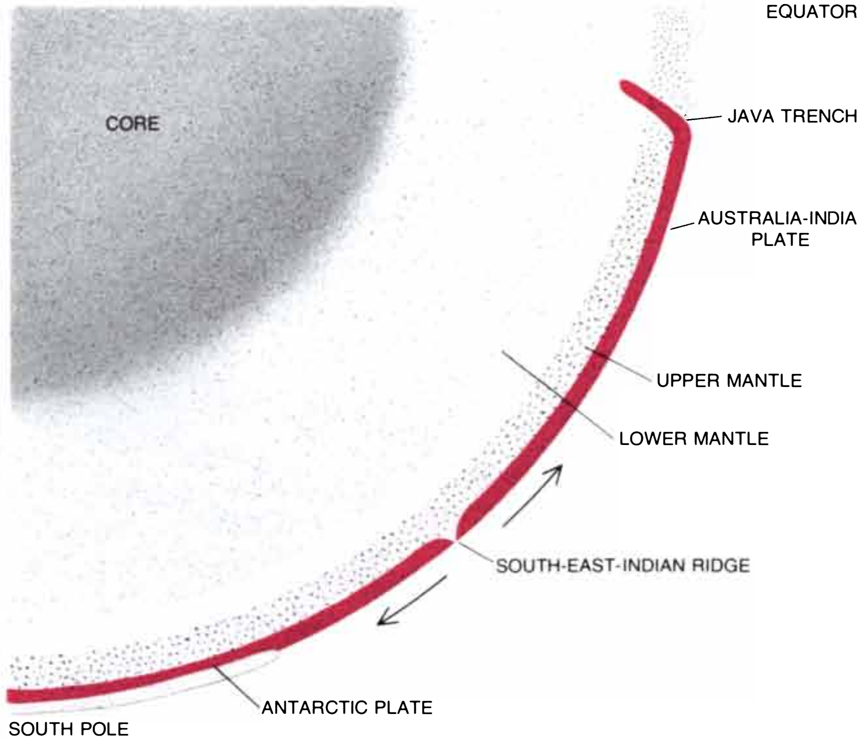
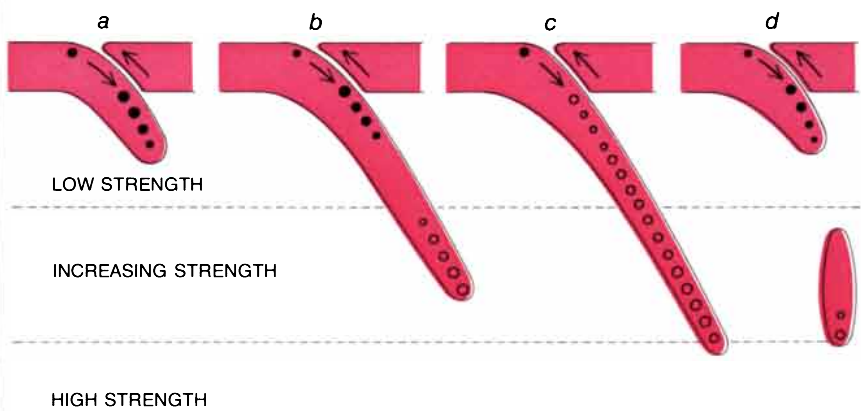


SECTION THROUGH THE EARTH depicts in true scale the configuration of plates from the Equator to the South Pole along the meridian at 110 degrees east. Plates (*color*) are created at mid-ocean ridges and usually descend into mantle at trenches adjacent to island arcs. Movement of plates transports by convection about half of the heat passing through upper mantle.

spheric disturbances are another example. Such flows are difficult to model and to understand.

The viscous material flowing in the earth's mantle has a very small Reynolds number, about 10^{-10}, and the momentum of the flow is negligible. One might expect convection in the mantle to be strongly influenced by the earth's rotation, but it can be shown that rotation has no direct effect. The Rayleigh number is of much greater significance because it is quite large. Although estimates vary, the lower limit is about 10^6, and the number could be higher by a factor of 10 or more. It is not difficult to produce such Rayleigh numbers in the laboratory by heating a fluid such as glycerin or silicone oil in a layer a few centimeters thick confined between two plates.

When the Rayleigh number in such a



DESCENDING PLATES meet increasing resistance as they penetrate deeper into the upper mantle. At a depth of 200 kilometers in *a* the slab is in tension and pulling apart, as is shown by solid dots. In *b* the upper section is still in tension but the part of the slab below 300 kilometers is in compression (*open circles*). In *c* the tip of the slab, below 600 kilometers, meets such resistance that the entire slab is in compression. In some cases (*d*) pieces of slab break off and sink to about 600 kilometers. Such observations suggest that the convective flow involving the motions of the plates is confined to depths in mantle shallower than 700 kilometers.

system is less than 1,708, thermal convection cannot occur; heat travels directly by conduction from the hot lower plate to the cool upper plate. If a small disturbance is created in the fluid, the disturbance dies away with time. Such a state is described as stable, but it need not be static. When the Rayleigh number is increased to between 1,708 and about 20,000, the system becomes unstable and small disturbances can grow into convection cells. The shape of the cells and their horizontal arrangement in the layer, called the plan form of the convection, depend on the form of the initial disturbance.

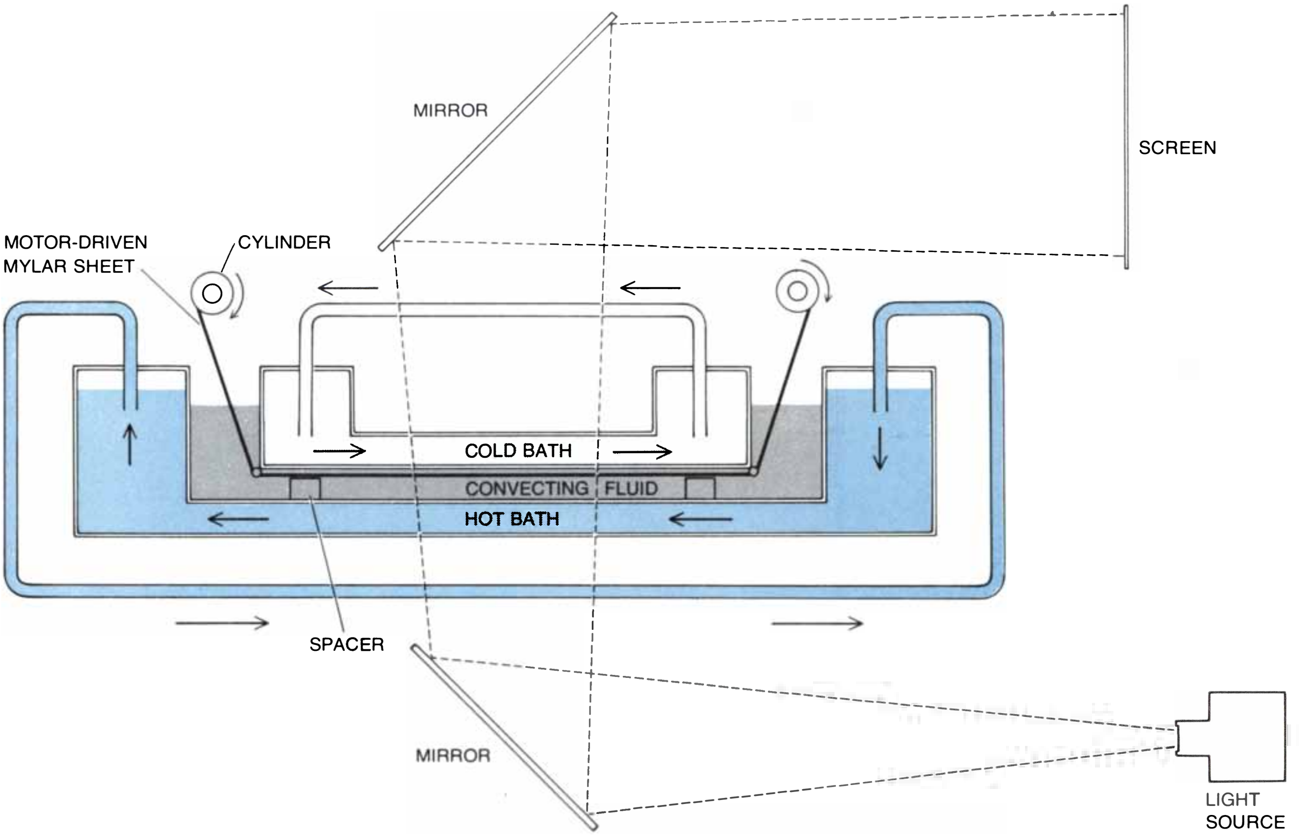
Types of Cells

The simplest plan form consists of two-dimensional cells: cylinders that rotate on their long axes. Three-dimensional cells can be produced by a three-dimensional initial disturbance. We know that in the range of Rayleigh numbers between 1,708 and 20,000 two-dimensional cylindrical cells are stable in the presence of small disturbances. We also believe all three-dimensional flows slowly evolve toward the two-dimensional configuration. We cannot be sure, however, because the evolution is very slow. Even experiments lasting several months have not completely resolved the question.

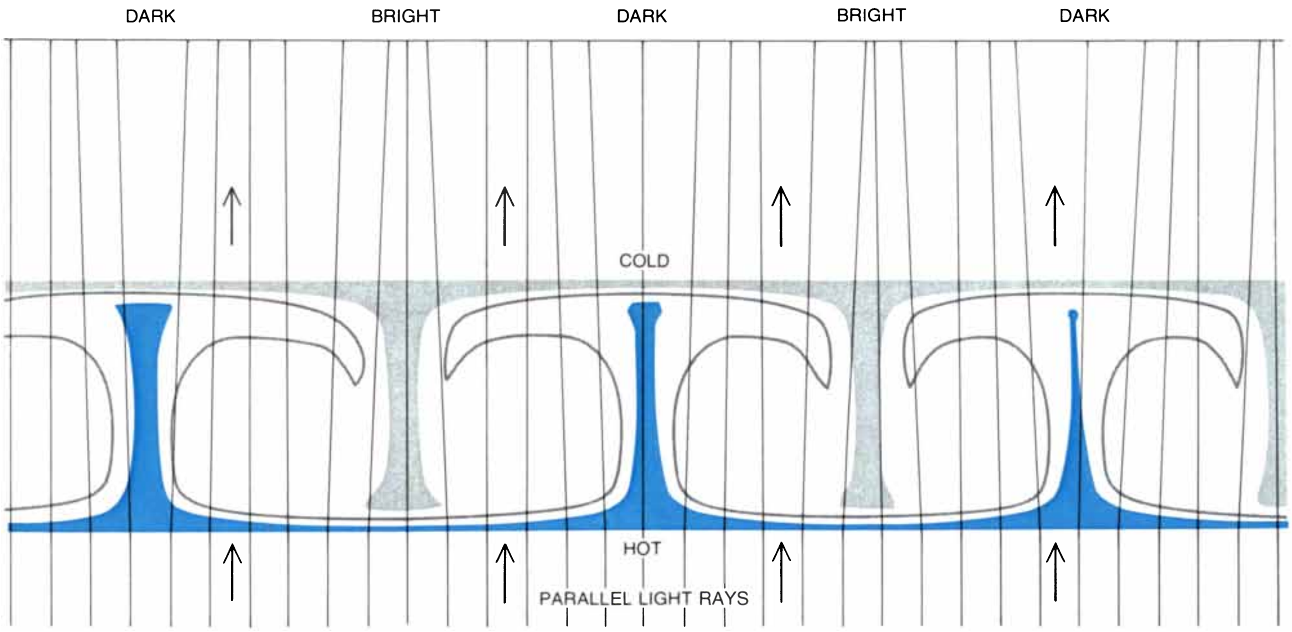
If the Rayleigh number is increased to 20,000 or so, two-dimensional cylindrical cells are no longer stable. Another set of cylinders at right angles to the original one grows to give rise to a three-dimensional network of rectangular cells, a pattern of flow called bimodal convection. If these cells are generated with great care in the laboratory, they are all virtually identical. Obviously if the plan form is not two-dimensional at the lower Rayleigh numbers where cylindrical cells are stable, there is no sudden shift to three-dimensional flow as the Rayleigh number is increased.

At Rayleigh numbers larger than about 100,000 the bimodal pattern breaks down in a rather complicated way. Where the two sets of cylindrical cells cross in the bimodal pattern there are points at which the fluid sinks or rises faster than it does elsewhere. As the Rayleigh number is increased these points move together and distort the bimodal pattern. The resulting plan form consists of a number of points of intense upwelling joined to one another by vertical sheets of sinking fluid (or points of downwelling joined by sheets of rising fluid). This plan form is called the spoke pattern.

What happens at still larger Rayleigh numbers, comparable to those of the material of the earth's mantle? This question is difficult to answer because the Reynolds number of spoke convection in laboratory experiments is the rel-



APPARATUS FOR CONVECTIVE FLOW simulates conditions thought to prevail in the earth's upper mantle. The convecting fluid is a viscous silicone oil, which is heated from below and cooled from above. The properties of the oil, in combination with suitable heat flows and depths of fluid, reproduce Rayleigh numbers in the range from about 1,700 to 10^6. The depth of the fluid can be varied from about 1.6 to seven centimeters. The convecting region measures about 100 centimeters on a side. To simulate the effect of a moving plate on the convection patterns a thin sheet of Mylar can be moved across the surface of the oil. Usually only a few hours are needed to reproduce events that would take millions of years on the scale of the earth. Light shining from below makes convection patterns visible.



SIMPLE CONVECTION CELLS, consisting of two-dimensional cylindrical cells, seen here end on, make a shadowgraph such as the one reproduced at the top of page 73. Parallel rays of light shine through the fluid from below. The rays are refracted away from hot regions and toward cold ones. Thus hot, rising sheets of fluid are marked by a dark line, which sometimes has a thin bright line on each side. Cold, sinking sheets of fluid are marked by a bright line. Convection cells in general tend to be as wide as they are deep.

atively large number of about 1, even when the fluid is very viscous, and momentum effects begin to become important. The convection becomes time-dependent, that is, its pattern changes with time. It still looks like the spoke pattern, but the hubs of the spokes are farther apart and the position of the rising and sinking sheets is constantly shifting. We suspect that this behavior occurs only when the Reynolds number is not small.

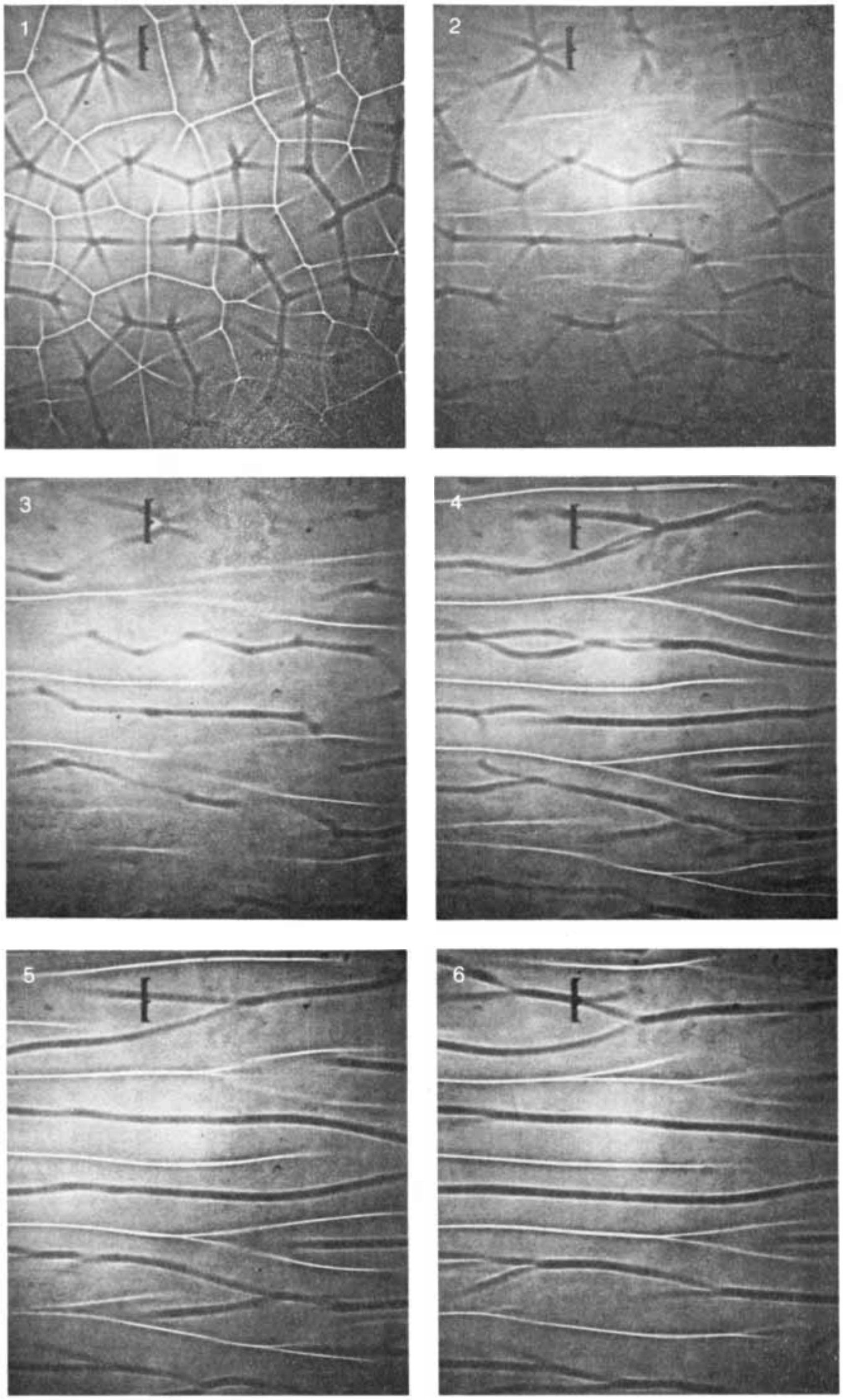
The most striking feature of the cylindrical, bimodal and spoke patterns is that the horizontal distance between the rising and sinking regions is always about the same as the depth of the layer. For a given difference in temperature between the bottom and the top of the layer, cells that are approximately square transport more heat than cells with other shapes. This behavior does not, however, offer much help in the effort to devise a model of the large-scale convection that moves the earth's plates (assuming that the flow in the mantle does not extend below 700 kilometers). What we should like to produce in laboratory experiments is convection cells whose width is many times their depth.

The Heating of the Fluid

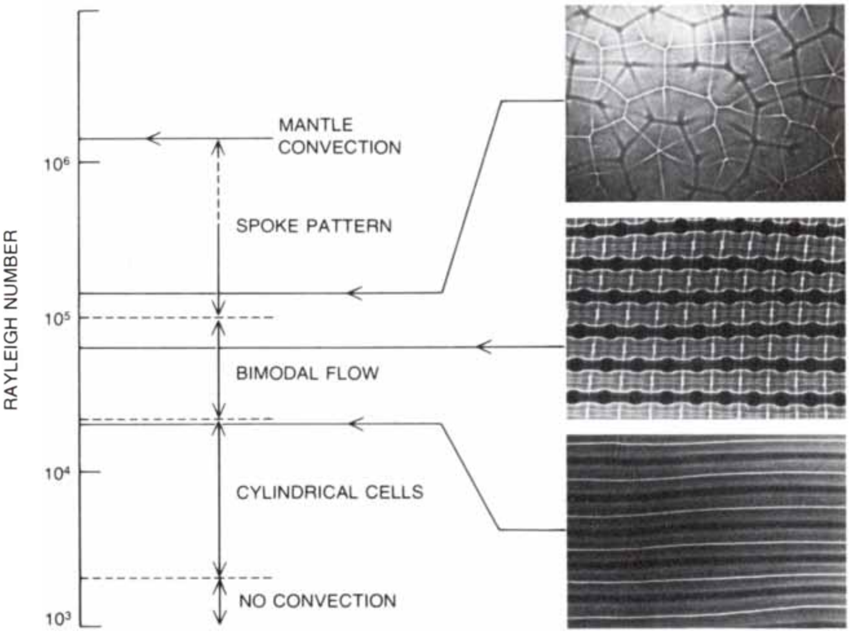
The mantle is not a uniform fluid heated from below. It contains radioactive elements, and their decay partly heats it from within. Moreover, the viscosity of the mantle material and its resistance to deformation vary sharply with temperature. It is because of this variation that the cool, thin plates that form out of the material are so rigid. Indeed, the variation is so great that many geophysicists question whether the mantle material can adequately be described as a viscous fluid. How seriously do such considerations complicate the effort to develop a model of the mantle's convective flow? It is true that most of the work done so far has involved fairly simple convection systems in which the fluid layer is heated only from below. Nevertheless, some significant discoveries about convection have been made, chiefly through experiments performed with computers.

As we have seen, when convection is driven by heating from below, heat is transported by hot jets or sheets of fluid rising from the lower boundary of the fluid and by cold fluid sinking from the upper boundary. At large Rayleigh numbers this type of flow gives rise to a thin horizontal layer of hot fluid adjacent to the lower boundary and a similar layer of cold fluid adjacent to the upper boundary. Between these two boundary layers is a region where there is little change in temperature from top to bottom. As the Rayleigh number increases, the turnover time decreases and the boundary layers become thinner. When the heat is generated internally, however, there is no lower boundary layer. Heat must be transported to the upper boundary by all the fluid's passing close enough to it for the heat to be conducted out. There is no longer a "passive" region in the center of the cell.

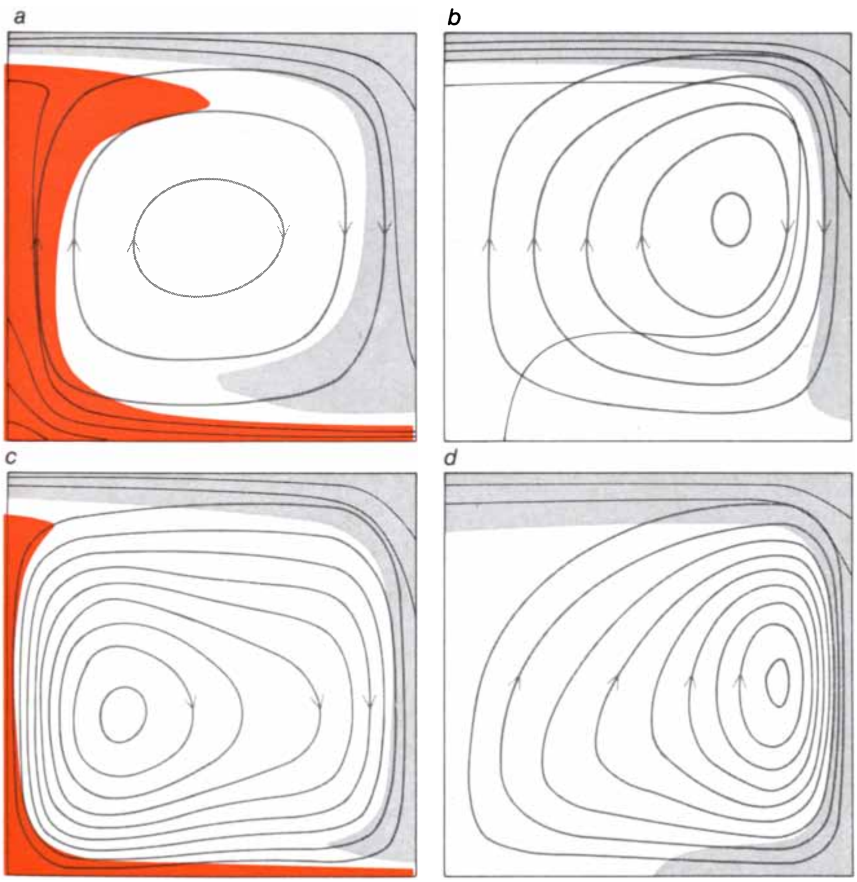
This state of affairs destabilizes the cold upper boundary layer and gives rise to complicated time-dependent behavior when the Rayleigh number exceeds about 40,000. Both jets and sheets of sinking fluid materialize spontaneously through instabilities of the upper boundary layer. Once they have formed



EFFECT OF SHEAR ON SPOKE PATTERN has been studied in the apparatus depicted on the opposite page. After a convective pattern characteristic of a Rayleigh number of 140,000 has become stabilized (*first picture*) the sheet of Mylar is set in motion to simulate a plate moving across the mantle. Successive pictures, made at equal intervals, show the rearrangement in pattern resulting from the motion of the Mylar plate as it travels from left to right. The shear converts the spoke pattern into cylinders whose axes are parallel to the direction of plate motion. The small black bar at upper left in each photograph indicates the depth of the fluid.



CONVECTION IN THE MANTLE is thought to involve Rayleigh numbers lying somewhere between 10^6 and 10^7. Laboratory experiments show that convection patterns develop in complexity from cylinders to bimodal flows to spoke patterns as Rayleigh number increases.



COMPUTER SIMULATIONS of convection cells show how patterns are affected by variations in fluid viscosity and by the mode of heating. When the viscosity is constant and the fluid is heated entirely from below (*a*), the rising and sinking sheets of fluid are nearly symmetrical. When the heat is supplied uniformly throughout the interior of a fluid of constant viscosity (*b*), convection consists of thin sinking sheets of cold fluid with hot fluid upwelling everywhere else. When the computer simulation is repeated for a fluid whose viscosity decreases markedly with temperature, heating from below (*c*) produces a convection cell in which the hot rising sheet is significantly thinner than the cold sinking sheet. When the heat is supplied from within variable-viscosity fluid (*d*), pattern is little changed from that seen when viscosity is constant.

they travel toward other sinking regions and combine with them in moving toward the interior of the fluid. The cycle is then repeated. The general form of the flow closely resembles the plate motions, with a thin, cold upper boundary layer and sinking sheets in motion, but the horizontal dimension of the motion is once again similar to the depth of the convecting layer.

In all the laboratory experiments the hot fluid is less viscous than the cold fluid, but this variation in viscosity only affects the flow strongly when the hot region is less viscous than the cold region by a factor of 10 or more. When the convection is driven by heating from below, the hot, low-viscosity, rising region becomes thinner and the sinking region broader than would be the case if there were little difference in viscosity. When the heat is supplied from within the fluid, there is no pronounced change in the form of the flow even where there are large differences in viscosity. The rather limited experiments on internal heating that have been conducted so far suggest that such heating has a more important influence on the form of the convection than differences in viscosity do. Recently computer experiments have been performed on convection in fluids that not only show variations in viscosity but also behave according to more complicated and more realistic laws of flow found by deforming rocks at high temperature. Somewhat surprisingly the introduction of these laws has little influence on the form of the flow.

Although there is clearly much more to be learned about the plan forms of convection in fluids of various viscosities or of convection driven by internal heating, all convection cells with a width five or more times greater than the depth of the convecting layer have been found to be unstable. Several workers have reported generating stable cells, but the flow was stable only because boundary-layer instabilities were artificially suppressed.

The Small-Scale Convection

One obvious way to reconcile the geophysical observations, which demonstrate that the cells extend at least 10,000 kilometers horizontally, with the laboratory and computer experiments is to assume that mantle convection extends from the surface to the region where the mantle meets the earth's core at a depth of 2,900 kilometers. There are several objections to such a model. The most important is the great resistance sinking slabs encounter at a depth of 700 kilometers. Another objection is more complex. If the flow extends throughout the mantle, it must be almost entirely driven by internal heating, which implies a Rayleigh number of at least 50 million. As we have seen, under these conditions many jets and sheets sink from the cold upper surface and the distance between them is only a small fraction of the depth of the convecting layer. To achieve conditions where this type of small-scale flow does not occur one must decrease the Rayleigh number by a factor of at least 1,000, or to about 50,000. Although our knowledge of the physical parameters of the earth's interior is not very precise, there seems no way to reconcile a figure of 50,000 with the estimated minimum value of 50 million required for deep convection in the mantle. We prefer a model in which the convection is confined to the mantle's outer 700 kilometers. The flow is then driven partly by heat generated within the fluid and partly by heat generated in the lower mantle and perhaps in the core, with the latter heat entering the base of the upper mantle by conduction.

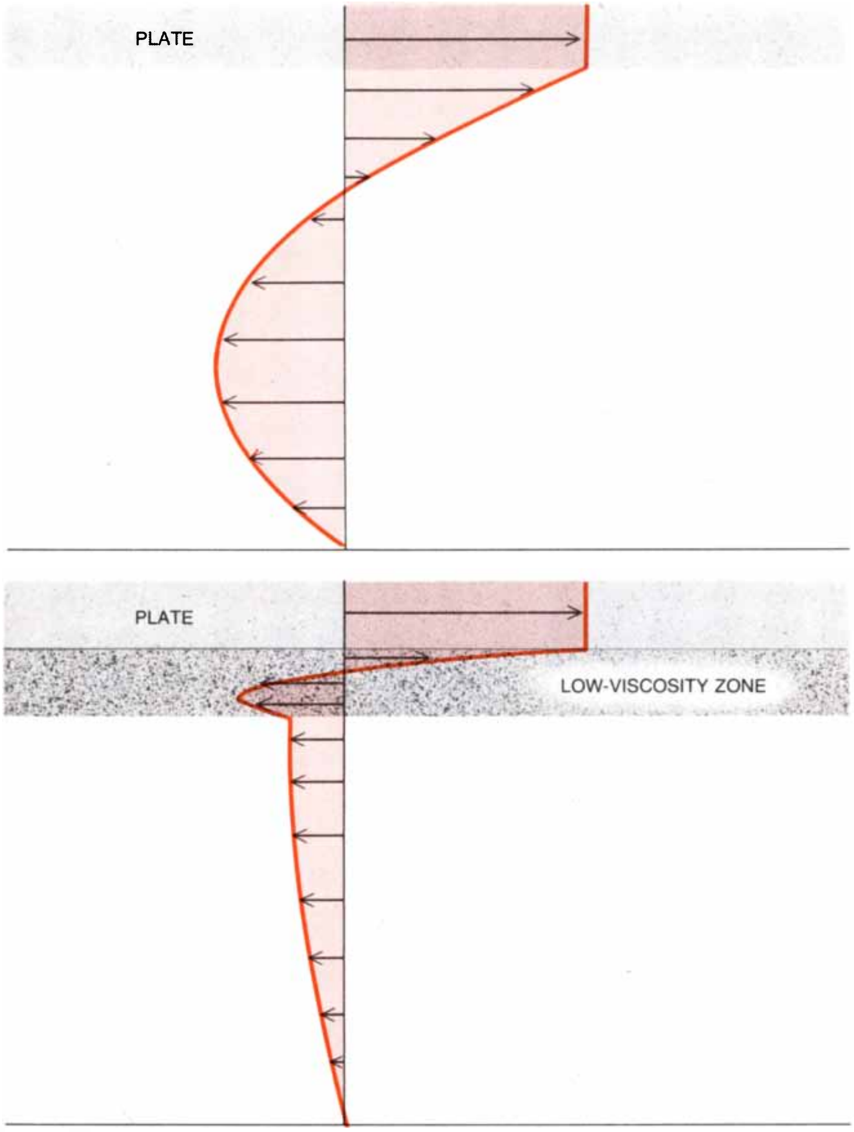
The experimental results clearly imply that there is small-scale convection in the upper mantle, with a distance of about 700 kilometers between the rising and sinking regions. In addition, however, there must be a large-scale convection to account for the geophysical observations, in particular the motion of the surface plates. Convection involving high Rayleigh numbers often occurs on several scales. The circulation of the atmosphere and of the oceans, driven by large-scale differences in density, provides familiar examples. In both cases large-scale motions are superimposed on small-scale convective features. Clouds are such a convective feature. Convection in the mantle, however, is quite different from the convection seen in the atmosphere and in the oceans because in the mantle the Reynolds number is small and momentum is unimportant.

To test the hypothesis that there are two scales of convective flow in the mantle we need geophysical evidence that the small-scale flow exists. One would also like to understand how the large-scale flow can be stable, as it so obviously is. The plan form of the small-scale flow probably depends on how strongly the surface plates and the mantle are coupled. If there is no slippage between a moving plate and the mantle, a substantial layer of the upper mantle will be dragged along by the plate. In that case the mantle under the moving layer will be strongly sheared.

We can simulate such a condition in our laboratory apparatus by arranging matters so that a sheet of the plastic Mylar, representing a plate, moves across the top of the convecting fluid at a steady rate. When the velocity of the plastic sheet exceeds a certain low value, the convection takes the form of rotating cylinders whose axes are aligned in the direction of the shear. The shearing merely transports the fluid along the cylinder and therefore has no effect on the small-scale convection. Convective cylinders in sheared flow are often seen in the atmosphere, where they take the form of cloud "streets": parallel rows of puffy clouds all about the same size. The shear required to change the three-dimensional bimodal or spoke patterns into cylindrical ones depends on the Rayleigh number. In the laboratory the cylindrical convection cells develop when the speed of the plastic sheet corresponds to a plate velocity of about 10 centimeters a year for a convecting layer 700 kilometers thick (assuming that there is no slippage between the plate and the mantle).

This general understanding of the physics of vigorous convection is obviously a great help in understanding convection in the earth's mantle. Instead of trying to apply the limited geophysical observations to guess the form of the flow, we can apply them to test models that are compatible with laboratory experiments. As we noted at the outset, however, the plates are so rigid they mask most of the effects that might be associated with small-scale convection. Two of the important effects that are not masked are regional variations in gravity and in the depth of the ocean.

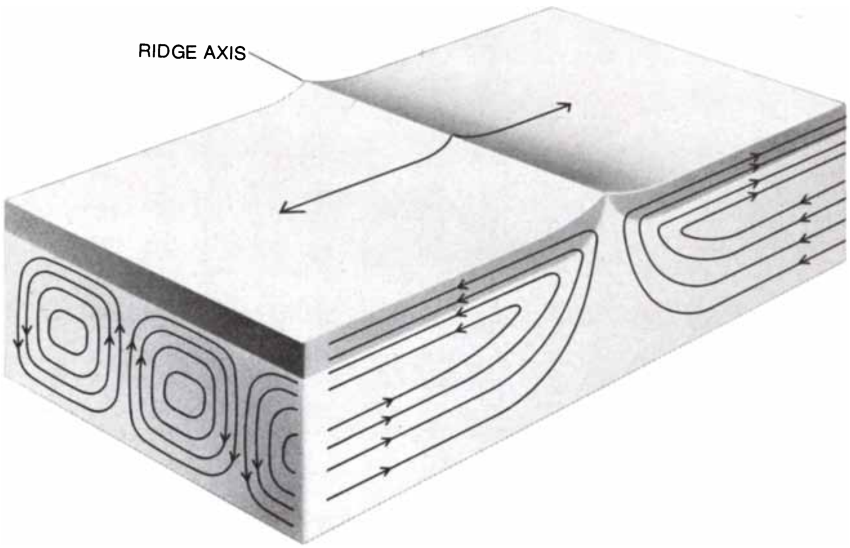
Gravity anomalies extending over a distance of 1,000 kilometers or more originate with differences of density in the mantle and associated deformations of the surface. Variations in the depth of the ocean are slightly less easy to interpret. The most obvious variation in depth results from the cooling and shrinking of a plate as it moves away from the axis of a mid-ocean ridge, where the growth of the plate begins



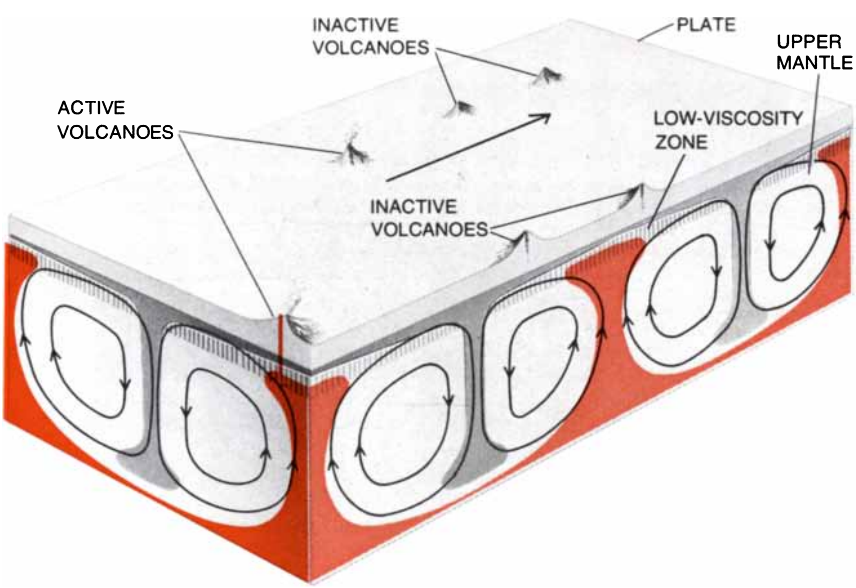
FLOW UNDER PLATES may follow either of two general schemes. In one model (*top*) the viscosity of the material under the plates is uniform. Thus a considerable layer of fluid is swept along by the plate motion. In order for mass to be conserved there must be a strong reverse flow deeper in the mantle. If, however, there is a thin layer of low-viscosity material under the plates (*bottom*), surface motions are decoupled from mantle and basically only mass of plates themselves need be carried by return flow. Geophysical observations favor decoupled model.

with the upwelling of hot material from the mantle. Because all plates cool the same way the depth of the ocean should be a function of the age of the plate material at that point, unless other forces are at work. The expected depth can readily be calculated. When this is done carefully, regional departures from the expected depth are revealed that correspond closely to the gravity anomalies. There are good reasons to believe the variations in depth and gravity are associated with convection currents at the base of the plates.

The first question we must answer is whether the moving plates sweep the upper part of the mantle along with them or whether they are decoupled from the convective motions in the mantle by a thin layer of low-viscosity material. If the plate motion sweeps much material along with it, there must be some kind of return flow at greater depth; otherwise mass would not be conserved. The return flow must be driven by a drop in pressure between the deep ocean trenches, where the plate plunges into the mantle, and the mid-ocean ridge. The required pressure difference should cause the top of the plate to slope. No such slope has been detected, and there is no obvious gravity anomaly produced by the material being carried into the trench and its return flow. Therefore the geophysical observations favor the decoupling of the plate from the mantle by a low-viscosity layer. The existence of such a layer was proposed independently of plate-tectonic theory to account for the observed damping of earthquake waves. The layer is conceivably created by the partial melting of rock between the crust and the mantle.



POSSIBLE MODEL OF CONVECTION under plates in the vicinity of a mid-ocean ridge visualizes flow on two scales. If the plates are moving apart fast enough, by 10 centimeters or more a year, the small-scale convection may be transformed into longitudinal cylinders with axes parallel to the plate motion. Exactly how the large-scale convection associated with the plate motion would interact with the longitudinal convection cylinders remains to be clarified.



ALTERNATIVE MODEL OF MANTLE CONVECTION may explain the creation of chains of volcanoes in which the site of active volcanism does not move as fast as the plates. This diagram attempts to show only the small-scale convection cells; the large-scale circulation is omitted. The small-scale flows are somewhat decoupled from the plates by a thin, low-viscosity layer that may be partially molten. Part of the heat needed to drive the small-scale circulation comes from the lower mantle and part from the decay of radioactive isotopes within the layer. Since the viscosity decreases with temperature the heat from below produces thin rising jets of hot material. The internal heating creates cold sinking sheets and jets, which dominate the overall flow. Because of the decoupling layer the hot rising jets can erupt as active volcanoes that do not move with the plate, whereas lava cones of extinct volcanoes do move.

The Decoupling of the Plates

Recent attempts to determine the forces acting on plates by analyzing their motions in some detail have also suggested that they are decoupled from the mantle. Little is known, however, about the viscosity of the layer responsible for decoupling, which is probably less than 50 kilometers thick. If the plates and the mantle are indeed decoupled, the resistance to plate motions is greatly reduced, and the various sources of convective energy associated with plate motions can easily provide enough power to drive the large-scale flow at the velocities observed. The most obvious source of energy is the upwelling of hot material from the mantle, which pushes the plates apart at the mid-ocean ridges. Even more important is the sinking of the cold, dense plates back into the mantle, which would tend to pull the plates toward the trenches.

There is little direct evidence of small-scale flow in the mantle. If the plates and the mantle are not decoupled, under plates that are moving rapidly such flows should take the form of rotating cylinders. If a low-viscosity layer provides decoupling, we expect the small-scale flow to be three-dimensional and complicated. We expect it to consist of both hot rising material and cold sinking material in the form of jets and sheets. Since roughly half of the convective layer's heat comes from conduction through the base of the layer and half comes from within, we expect more sinking regions than rising ones, and we also expect the variation of viscosity with temperature to make the rising flows narrower than the sinking ones.

Attempts have been made to detect the small-scale convection, but they have met with only marginal success. Not all geophysicists accept the gravity

DP Science Dialogue

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

The mid-module of an F-14 fighter is wheeled out of the Grumman plant at Bethpage, N.Y.

211 Integrated Programs Speed Aerospace Design at Grumman

Time is usually in short supply in the aerospace industry. Because most development contracts call for completion by a fixed date, adherence to the planned schedule is crucial. And few categories of aerospace engineering are more demanding than airframe analysis and design; drawings must be released on time, and later changes in structure are very costly.

The need for these changes can often be traced to faulty communication between groups of engineers working on related tasks. Ten years ago Grumman Aerospace Corporation of Bethpage, N.Y., pioneered a computerized integrated engineering system. Today its successor, the far more sophisticated Rapid Aerospace Vehicle Evaluation System (RAVES), has become an indispensable resource of Grumman's Engineering Department.

RAVES is a collection of 211 programs, such as Mission Analysis, Maneuver Loads, and Flutter Analysis, "chained" or integrated so that each one generates data directly usable by the programs that follow. They cover the design process from preliminary work to

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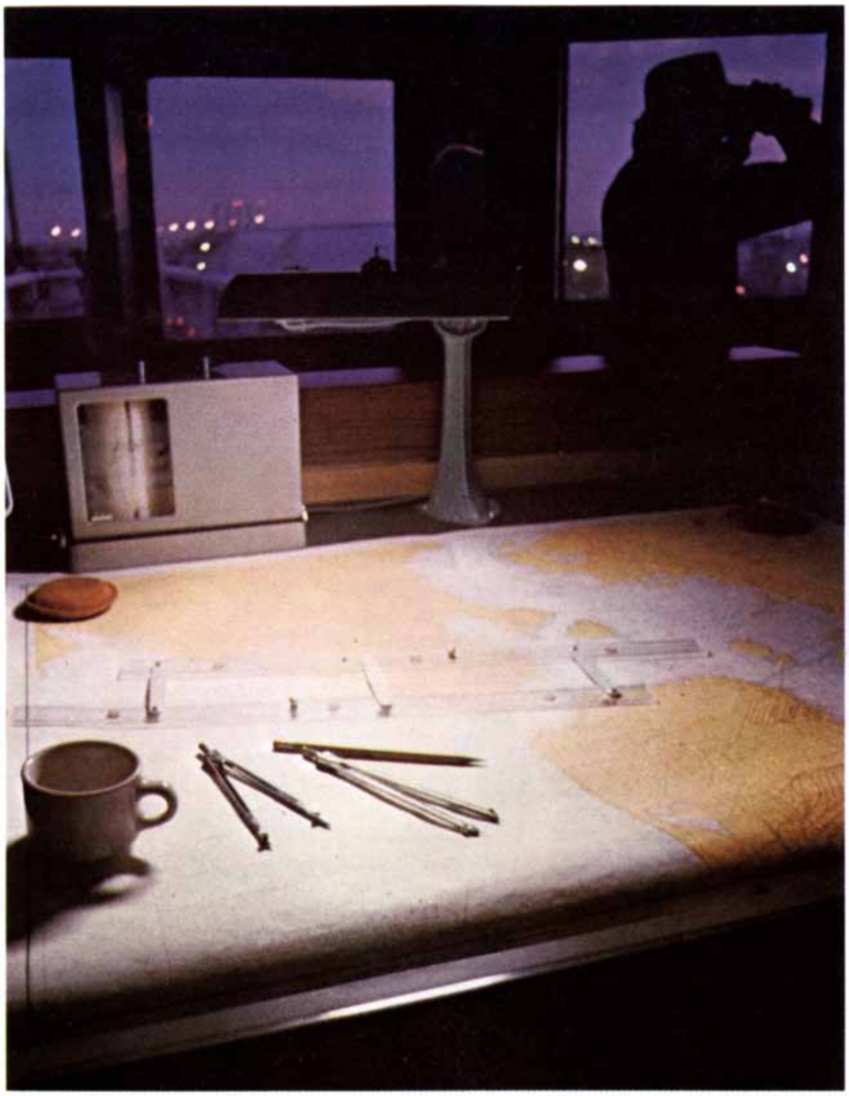
Magnavox Gets Precise Fixes with 20-Hour Simulations



View from the bridge of a large tanker. Ocean-going merchant vessels now use shipboard electronic systems, interpreting signals from earth satellites, to obtain precise navigational fixes automatically.

A ship on the open ocean can now obtain an instant fix on its location to within a few hundred feet, in any weather. A new Magnavox Marine Navigation System uses signals from six earth-girdling satellites of the Navy Navigation Satellite System (NNSS) in orbits that bring them in range of any point on earth from one to four times every two hours.

Such shipboard systems—which have given Magnavox a leadership position in the fast-growing field of satellite navigation—originate at the Magnavox Research Laboratory in Torrance, California. There engineers make extensive use of an interactive IBM computer system for the demanding research involved in satellite-related projects.

"Simulations requiring 20 hours or more of computer time are not uncommon," says Gregory Owen, data processing manager. "These range from models of fluctuating signal conditions—noise, 'ghost' transmissions, and the like—to simulated navigational geometries required to determine system accuracy under all possible conditions. Of our 225 engineers, at least 140 are now active computer users, compared with only 20 two years ago. They log about 3,200 hours of connect time monthly from fourteen interactive IBM visual displays and two hard copy terminals. And they access as many as 200 programs stored on IBM 3350 disks. We're constantly adding disk space as program use grows."

Engineering work runs on an IBM System/370 Model 145 under Virtual Machine Conversational Monitor System (VM/CMS) for sixteen hours starting at 8 a.m. (The company's commercial and accounting work is done in batch mode.) Of all work handled by the computer, 70% is interactive engineering.

"We've experienced a 50% gain in engineering productivity with interactive computing," says Andy Chao, manager of research. "The engineers accepted it rapidly—beyond all our expectations, in fact—because they found it met their needs in a way they'd never experienced before. Another factor is ease of learning—it takes only two hours to become familiar with the system."

And Dr. Charles Cahn, associate director of advanced programs, points out that the IBM system puts emphasis on the personalized aspects of computer use.

"Engineers can develop their own programs in interactive programming languages like FORTRAN and VS BASIC," he points out. "They can go ahead and use their own programs whenever they need them, or call up the standard programs in our library.

"This bypasses the usual development cycle, saving weeks or months. We think it's a great way to run an engineering laboratory."

Grumman...

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release of finished drawings and data. Engineers use terminals throughout the company, guided by question-and-answer procedures, to execute programs on the IBM System/370 Model 168.

"Because of constant advances in engineering and technology, we're doing more and more analytical work on each new project," says Glen Wennagel, RAVES project engineer. "At the same time, today's requirements for documentation are far greater. The result could have been an explosion in engineering man-hours—if it were not for the time saved by the computer.

"Now we have found that certain analysis costs have been reduced by 75%. Typically, an engineering program makes possible enough man-hour savings in less than one year to pay the cost of developing it."

Another set of programs, called Grumman Engineering and Manufacturing Systems (GE/MS), interfaces with RAVES to develop the actual geometry of an aircraft. Engineers use interactive graphics and work with a light pen and keyboard to create designs and drawings and apply specifications to basic geometric models on the screens of IBM 2250 Display Units.

"GE/MS can save up to 50% of the time required to produce a finished drawing," says Paul Wiedenhaefer, program director. "Interactive techniques in design, drafting, and manufacturing have become a cost-effective way of life at Grumman."

Endangered Plants Get Help from the Computer

Because of man's steady encroachment on the environment, hundreds of plant species in the United States may face early extinction. The Office of Endangered Species of the Department of Interior issues periodic lists of "threatened" or "endangered" species. But protective action is largely up to individuals.

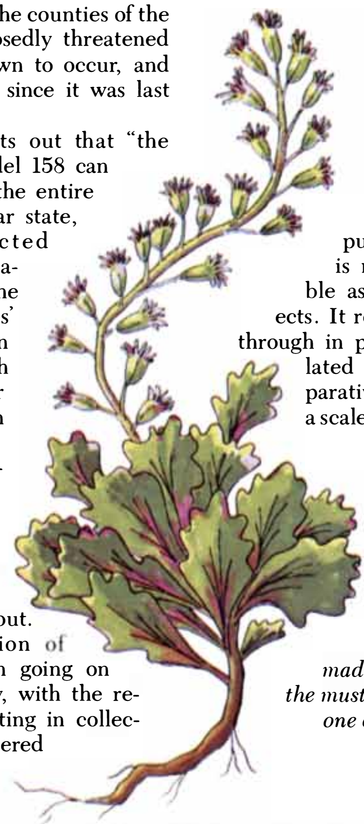
Now botanists have a natural ally in the computer, which is being used to make existing data on plants, including endangered ones, far more accessible and useful.

Under the direction of Theodore J. Crovello, professor of biology at the University of Notre Dame near South Bend, Indiana, data on over 100 species of the mustard family found in the U.S. has been entered into the computer. This is one of the first attempts to computerize a monograph on plants. Data on over 35,000 individual collections of mustard plants preserved in museums across North America has been captured in the Notre Dame data bank.

"Although this data has been available for decades, we had to wait for the computer as the medium through which we could rearrange and analyze it efficiently," says Dr. Crovello. "Now we can determine in seconds the counties of the U.S. in which a supposedly threatened species has been known to occur, and how long it has been since it was last collected."

Dr. Crovello points out that "the IBM System/370 Model 158 can swiftly print maps of the entire U.S., or of a particular state, according to selected criteria, such as the relative similarity among the counties of the species' distribution. And it can answer questions such as, 'At what time of year is this species in flower?'

"There are an estimated 250,000 species of vascular plants in the world, 20,000 of them in the United States," Dr. Crovello points out. "Modern classification of these plants has been going on since the 18th century, with the resulting data accumulating in collections and catalogs scattered all over the world.

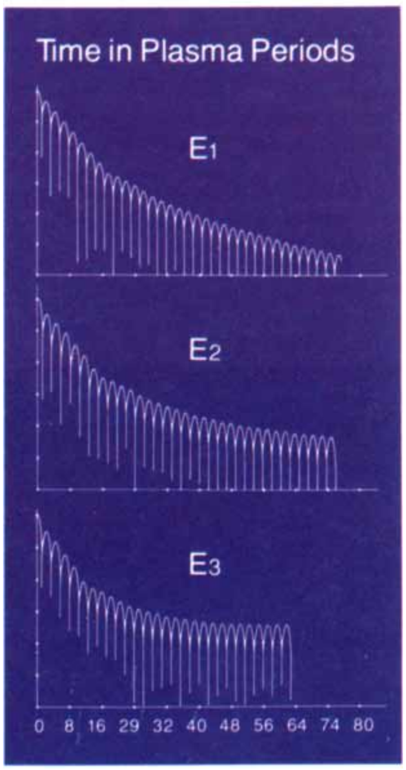


"Inevitably, such data varies greatly in precision and completeness, presenting real difficulties of nomenclature and missing information. Nevertheless, the development of large computerized plant data banks is now demonstrably feasible as shown in several projects. It represents a major breakthrough in plant systematics and related fields, permitting comparative studies of plant life on a scale not hitherto practicable.

"And it might possibly help to preserve some of the many rare species now in danger of vanishing from the earth."

The Notre Dame computer data base is made up of over 100 species of the mustard family found in U.S., one of which is the threatened Streptanthus hispidus shown here.

Research in Fusion: Computer Simulated Plasmas



Computer simulation of the "damping effect" of energy waves moving through plasma. At high wave energy level (E3), the slope is greater than at lower levels (E1 and E2).

Controlled thermonuclear fusion is a possible solution to the energy crisis. Atomic particles release great quantities of energy as they collide and "fuse" at million-degree temperatures. The basic fuel for the process is deuterium, an isotope of hydrogen, which is plentiful in seawater. And controlled fusion is intrinsically safe because any breakdown in the reactor stops the process. Although in theory nuclear fusion has highly desirable properties as a source of energy, twenty-five years of development effort have not produced a practical reactor for power plant use.

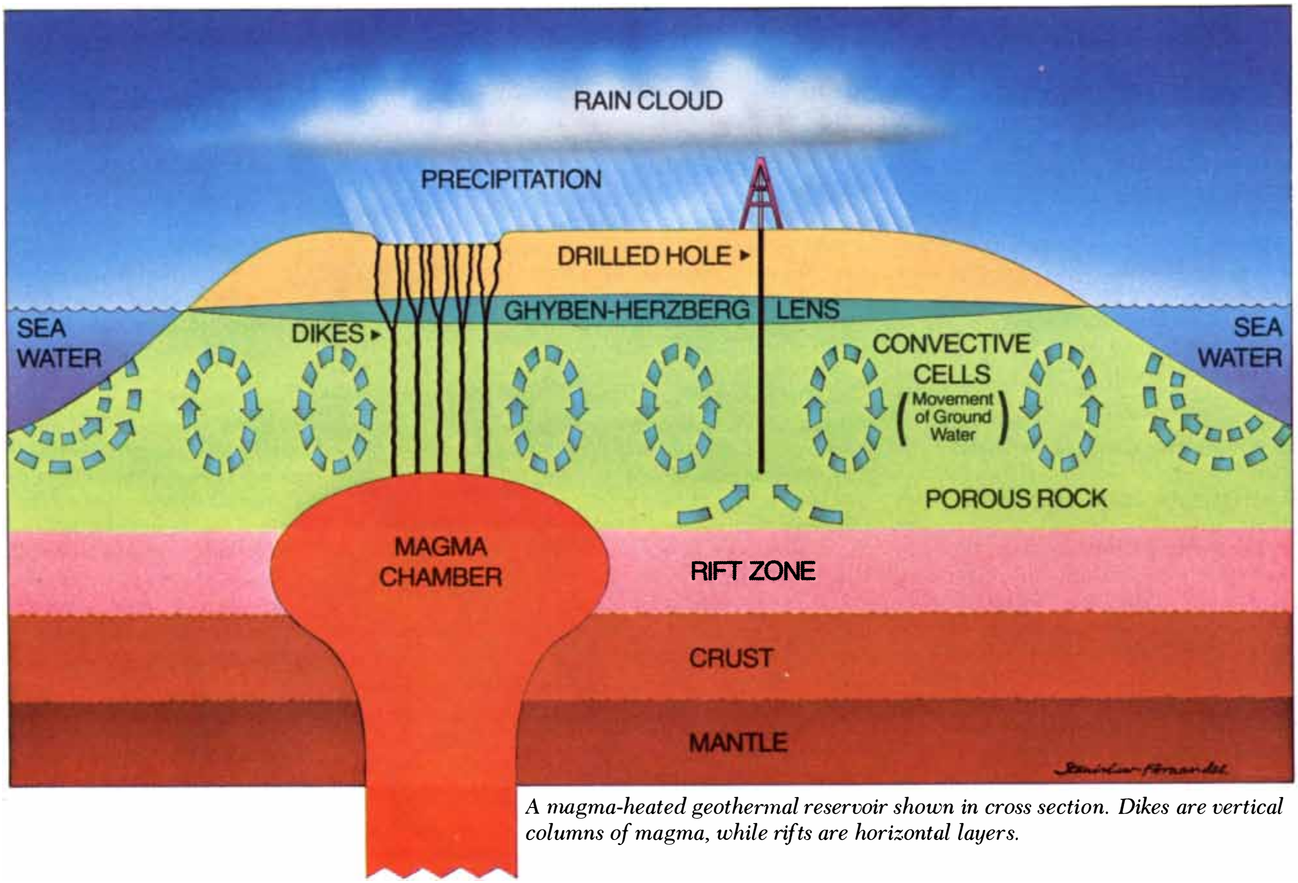
At the IBM Scientific Center in Palo Alto, California, theoretical studies using computer simulations have helped shed light on the behavior of plasmas, or superheated gases—one of the most critical and fundamental areas of fusion research. In a plasma, the gas is so hot and the atomic particles are moving so fast that normal electrical forces are overcome as the particles collide, fuse and release further energy.

IBM scientists used the computer to build mathematical models of plasma. The simulations offer a valuable alternative to the costly and difficult process of creating plasmas in the laboratory.

The work at Palo Alto is based on an equation describing the behavior of plasmas first written by a Russian scientist, A.A. Vlasov, in 1944. The Vlasov equation is still widely regarded as accurate. However, the equation—in seven variables—is unsolvable by conventional methods.

The IBM researchers reduced the number of variables by treating wave propagation in the plasma as one-dimensional. With this simplification, they were able to compute the damping effect or the rate of decay of waves moving through the plasma.

These results—and, by extension, the computational technique—have been confirmed in laboratory tests with real plasmas. Computer-simulated solutions to the Vlasov equation describe plasma behavior as observed in the laboratory in great detail. In the future scientists will be considering broader and more ambitious applications of the computer to plasma physics. The next step would be to model wave propagation in the plasma in two dimensions with equal accuracy.



A magma-heated geothermal reservoir shown in cross section. Dikes are vertical columns of magma, while rifts are horizontal layers.

Harnessing Geothermal Energy in Hawaii

Thousands of feet below the volcanic island of Hawaii (the "big island" of the Hawaiian Chain), geologists believe there may be a huge pool of hot water, possibly superheated.

Water normally boils at 100 degrees centigrade, but superheated water, subjected to great pressure in the ground, will stay in liquid form at about 200 degrees until brought close to the earth's surface, where it will flash into steam. The steam from such a geothermal reservoir could drive a turbine to generate electricity. In fact, the island's supply of electricity might one day be doubled in this way.

The realization of this possibility is the goal of the Hawaii Geothermal Project being conducted by a group of scientists who are making use of computer modeling and simulation at the University of Hawaii. The scientists are drilling a shaft more than a mile deep south of the city of Hilo, where they hope to reach water heated by vertical columns ("dikes") of molten rock, or magma. Helping to guide them is a computer-generated mathematical model of the subterranean features of the island.

The model was created by Dr. Ping Cheng, professor of mechanical engineering, to determine the probability that a geothermal reservoir does exist and what its characteristics are likely to be. Varying conditions—such as differences in the size, temperature and location of the heated areas—were then applied to the model in the form of nonlinear partial differential equations. Based on the equations, the university's IBM System/370 Model 158 produced initial predictions about the temperature distribution and convection patterns of ground water in the reservoir. Later information obtained from the actual drilling is used to modify and refine these analyses.

What if the water is not hot enough to produce steam? In that case another but more expensive technique, the binary fluid method, may be used. In this method the hot water heats a second liquid, a refrigerant, which has a lower vaporization point than the water. Here again, the computer is of aid.

"Computer modeling enables us to determine the costs associated with each method at every given temperature," says Dr. Deane Kihara, associate professor of mechanical engineering. "We work with over 25 variables, including such factors as the capital investment associated with each type of refrigerant, the flow rates and the optimal size of each physical component of the generating plant."

Disposal of the cycled water is another area under investigation with computer aid. Since it is likely that water from geothermal reservoirs will contain minerals and salt, the effluent should not be dumped untreated either on the surface of the island or into the sea. Reinjection into the earth is currently being considered, with the expense and geological consequences as parameters.

"At the very least, the Hawaii Geothermal Project will add to our geological knowledge of the islands," says Dr. Paul Yuen, associate dean. "And if we are successful, we may be able to lower the high cost of electricity on Hawaii."

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

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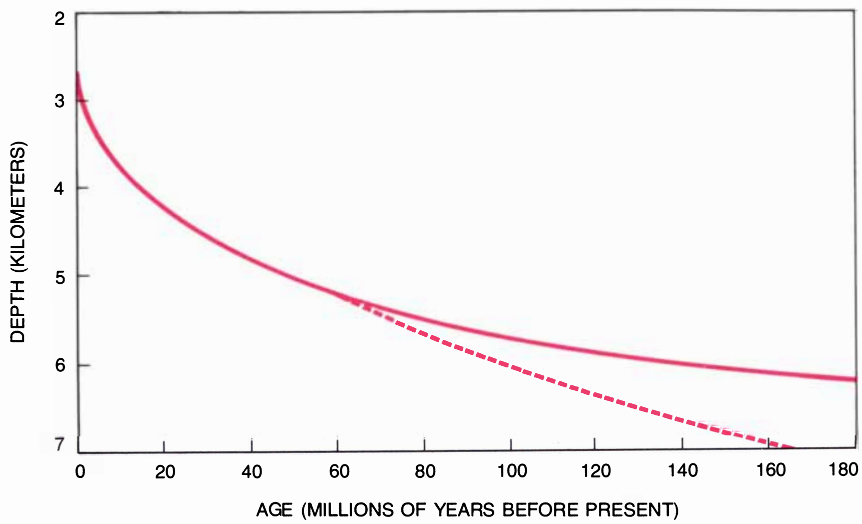
anomalies and depth variations as convincing evidence for small-scale flow. Nevertheless, there is good evidence for some type of convective heat transport other than that directly associated with the plate motions. The increase in the depth of the ocean with the age of the plate at the bottom agrees closely with the subsidence calculated for a plate about 120 kilometers thick. If the mantle below a depth of 120 kilometers could cool by conduction, the oldest parts of the Atlantic and the Pacific would be about a kilometer deeper than they actually are. Such cooling can be prevented only if heat is transported to the base of the plate by convection. The ocean-depth observations do not, however, supply any information about the plan form of the inferred convection. Although it seems likely that small-scale convection of the type we have described is responsible, any form of convective heat transport would account for the observations.

There is one other set of observations that offers evidence for both decoupling and small-scale convection: the chains of volcanoes that form ridges in parts of the deep ocean. The best-known example is the Hawaiian Ridge in the Pacific. The two currently active volcanoes are on the island of Hawaii at the southeast end of the ridge. The volcanic rocks that form the ridge increase steadily in age with their distance from Hawaii. Several ridges in the Indian Ocean and the Atlantic resemble the Hawaiian Ridge.

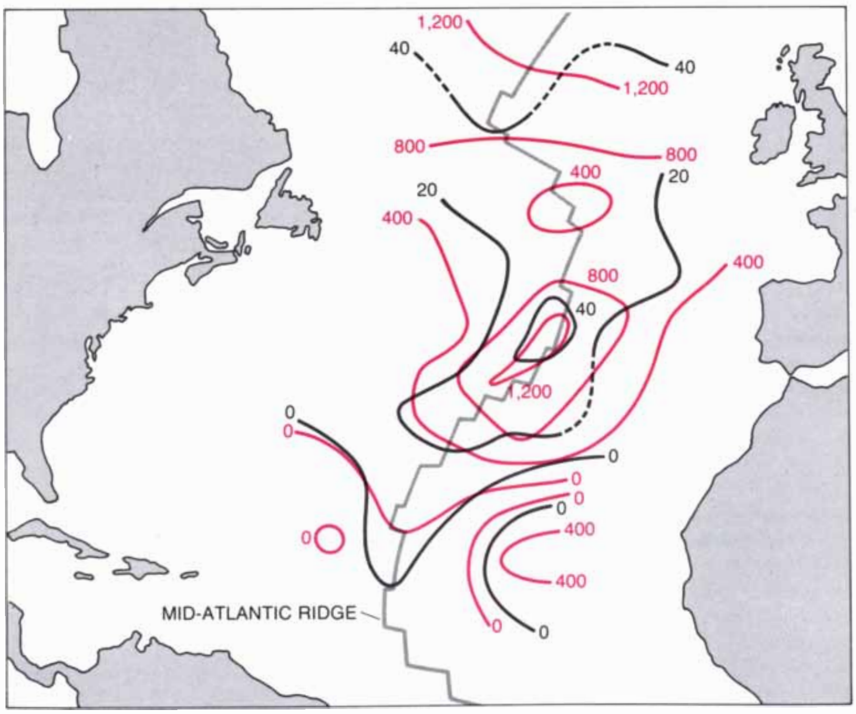
The interesting point is that the motion of an active site of such volcanism with respect to another active site is only one or two centimeters a year, whereas the motion of one plate with respect to another is more than 10 centimeters a year. These measurements indicate that the source of the lava for the volcanoes lies under the plates and does not move with them. According to this view, the volcanoes are the surface expression of jets of hot material that rise to the surface from the base of the mantle.

The principal objection to this concept comes from the computer models of the behavior of internally heated fluids, which show that although sinking cold jets are generated, hot rising ones never are. No such difficulty arises, however, if convection is confined to the upper 700 kilometers of the mantle. Since this region is heated both from below and from within, hot jets should be able to form in it. Furthermore, such jets will not move with the plates, because they are decoupled. On the basis of the laboratory experiments one would expect the small-scale convection to be time-dependent. Hence it is not surprising that there is a certain amount of slow movement in the jets that have given rise to the volcanoes of the oceanic chains.

We should obviously like to have more information about the form of the small-scale flow, but it is nonetheless pleasing that we can account for all the relevant geophysical observations with a model based on laboratory experiments. The fact remains that the observations are all too few. With recent advances in the measurement of the earth's gravity by satellites, however, our knowledge of the gravity anomalies under the oceans should increase rapidly over the next few years. And laboratory experiments at large Rayleigh numbers (10^6 to 10^7) and small Reynolds numbers are possible, although difficult, and they should help us to understand the features detected by the satellites.



DEPTH OF THE OCEAN increases with the age of the sea floor because of thermal contraction as the plate cools from a high uniform temperature at the axis of the mid-ocean ridge. If the cooling continued uniformly with age as the plate moved away from the ridge, the depth of the ocean should follow the broken curve. Actual depth measurements, however, yield solid curve, which conforms to cooling of plate 120 kilometers thick whose base is at 1,200 degrees Celsius. It appears that heat is supplied from below, probably by small-scale convection.



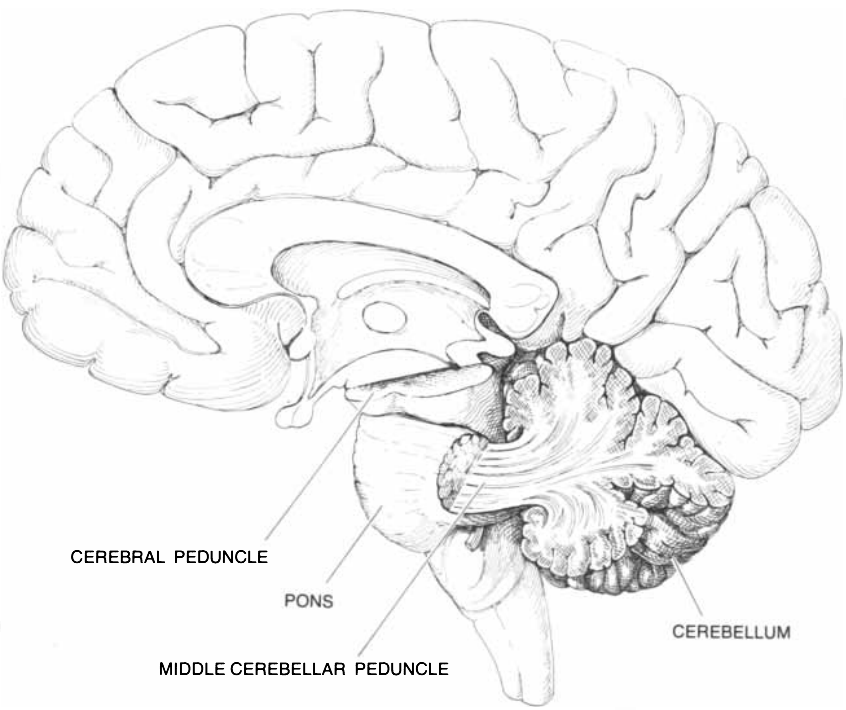
DEPTH OF THE NORTH ATLANTIC is shown in meters (*color*) after removal of the effect of cooling of the plate by age. Black lines show contours of the gravity field in milligals. The variations in the two features seem to be closely related and could be evidence for a region in which hot mantle material is carried upward by small-scale convection currents. Neither the depth of the ocean nor the gravity field seems to bear much relation to Mid-Atlantic Ridge (*gray line*), where the North American plate and the Eurasian plate are being pushed apart.

Visual Cells in the Pons of the Brain

Cells in a protuberance at the base of the brain act as a major relay in the circuit that links the eyes and the muscles to guide the movements of the body

by Mitchell Glickstein and Alan R. Gibson

Tasks that demand close coordination between eye and limb, such as a man catching a ball or a cat chasing a mouse, call for the combined activities of visual and motor centers in the brain. In mammals these centers are located in circumscribed regions of the cerebral cortex, the great folded sheet of nerve cells that forms the major part of the cerebrum. The visual area is at the back of the cortex; electrical stimulation of the area produces the sensation of light, and the cells of the visual cortex can be selectively activated by presenting visual stimuli to the eye. By the same token stimulation of the motor area in the forward part of the cortex gives rise to muscular contraction, and the activity of cells in the region increases in a brief period before muscular movement. How do the visual and motor cortexes interact to guide the movements of the limbs? What kind of connections are there between them?



PONS OF THE HUMAN BRAIN was first described by the 16th-century Italian anatomist Constanzo Varolio, who thought it resembled a bridge ("pons" in Latin) arching over the brain stem. The cerebral peduncles contain fibers that originate in the cortex of the cerebrum and project to the pons. From there they travel through the middle cerebellar peduncles to the cerebellum, where sensory information and motor information are combined to guide the limbs.

The cerebral cortex, like the rest of the brain, is made up of billions of unitary components: the nerve cells, or neurons, and their supporting cells. Neurons come in many different sizes and shapes, and most of them have an elaborate system of branching fibers, the dendrites, and a single long fiber, the axon. It is along the axon that the neuron transmits messages to other nerve cells in the form of electrochemical impulses. The far end of the axon makes contact with a dendrite or the cell body of another neuron; the specialized junction where the transfer of impulses occurs is the synapse. The synapse allows information to flow in only one direction, and nerve cells are organized into circuits by their synaptic connections.

Our knowledge of the circuitry linking nerve cells in the visual and motor regions of the cerebral cortex is meager, but it is possible to trace at least three anatomical pathways by which connections might be made. One such pathway is entirely cortical: information in the visual cortex passes through the visual association areas, where it is processed, and then proceeds to the motor cortex. The other two routes leave the cerebral cortex and then return, one route by way of the basal ganglia, the other by way of the cerebellum, the "little" brain that governs the coordination of the motor system.

This latter pathway is of particular interest, because a good deal is known about the internal workings of the visual cortex and the cerebellum but much less about the connections between them. With our colleagues at Brown University and the University of Oxford we have been studying the first relay in a pathway that begins in the visual cortex and connects to the motor cortex by way of the cerebellum, a circuit that appears to be one of the important pathways for the visual guidance of movement.

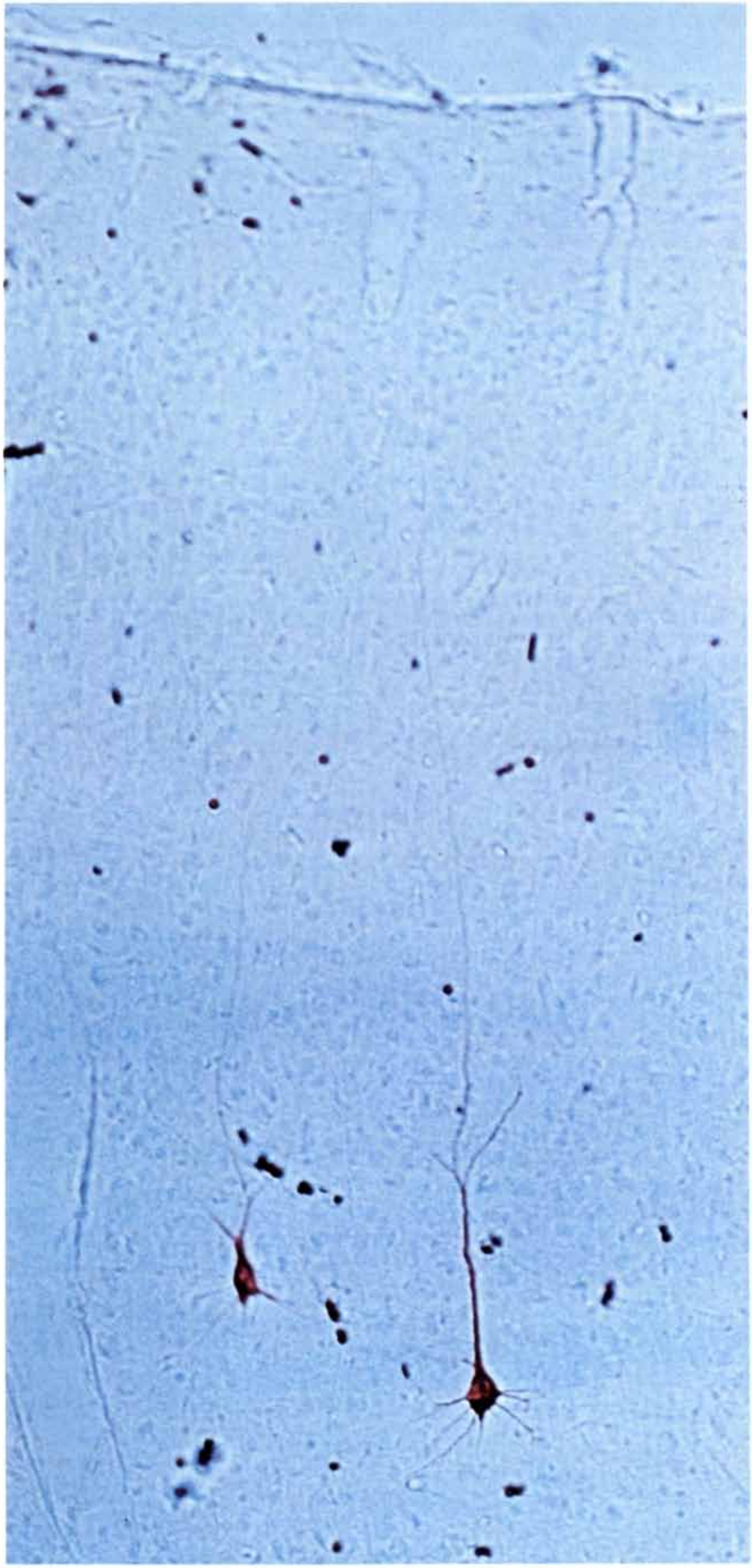
Early workers thought that only the

motor cortex sent fibers to the cerebellum. Some 25 years ago Ray S. Snider, who was then working at Northwestern University, found evidence for a functional visual input to the cerebellum when he observed that flashes of light could evoke potentials in the vermis, the middle part of the cerebellar cortex. Subsequent work has confirmed Snider's observation, and it has also revealed that in a lightly anesthetized experimental animal a bright flash can evoke potentials over nearly all of the cerebellar cortex. The visual input to the cerebellum is relayed through the visual cortex and also through the superior colliculus, a visual structure in the midbrain.

The connections between the visual cortex and the cerebellum are part of a massive fiber system that includes output fibers from almost every region of the cerebral cortex. The outflowing cortical fibers do not go to the cerebellum directly but are relayed by a protuberant structure at the base of the brain. This structure was described by the 16th-century Italian anatomist Constanzo Varolio, who was the first to dissect the brain from below. He thought the great transverse fiber bundle overlying the protuberance resembled a bridge, with the brain stem flowing under it like a canal, and he named the region the pons, from the Latin for bridge. In those mammals with a large cerebral cortex the pons and the cerebellum are also prominent; all three structures are strikingly developed in the human brain.

The pathway connecting the visual cortex to the cerebellum by way of the pons interested us and our colleagues for several reasons. First, since the cerebellum plays an important role in the control of movement, we felt that analysis of its visual input might reveal the nature of one of the major circuits involved in visual-motor guidance. Second, we believed that examining the connections between the visual cortex and the pons would help us to clarify another problem concerning the representation of the visual world in the visual cortex.

It has been known for some time that



CORTICOPONTINE CELLS (cells in the visual cortex of the brain that project to the pons) are selectively stained reddish brown by the technique of horseradish peroxidase. This photomicrograph shows a section about 1.5 millimeters deep into the visual cortex of a cat; the line at the top is the surface of the brain. Some of the fibers projecting from the two stained cells are clearly visible, but the single fibers that connect the cells to the pons are too fine to be seen at this magnification. Corticopontine cells are few in number and are confined to a deep layer of cortex with major outputs to the lower brain structures.

light impinging on the retina is coded into nerve impulses by the retinal cells and transmitted over the optic nerve to the lateral geniculate bodies. These structures are the main way stations between the eyes and the visual cortex, and each receives an input from half of the visual fields. In cats the lateral geniculate body projects to several regions of the visual cortex, among them the areas in the cat brain designated 17 and 18. Each of these areas embodies an independent representation of half of the visual fields.

Why are the visual fields mapped in parallel onto two different areas of the cortex? If it is because these areas have different functions, their differences might be reflected in the nature of their outputs. For example, one area might show a heavier projection of fibers to the pons. If that were the case, it would have rather direct connections to the cerebellum and might therefore be specialized for the visual guidance of movement.

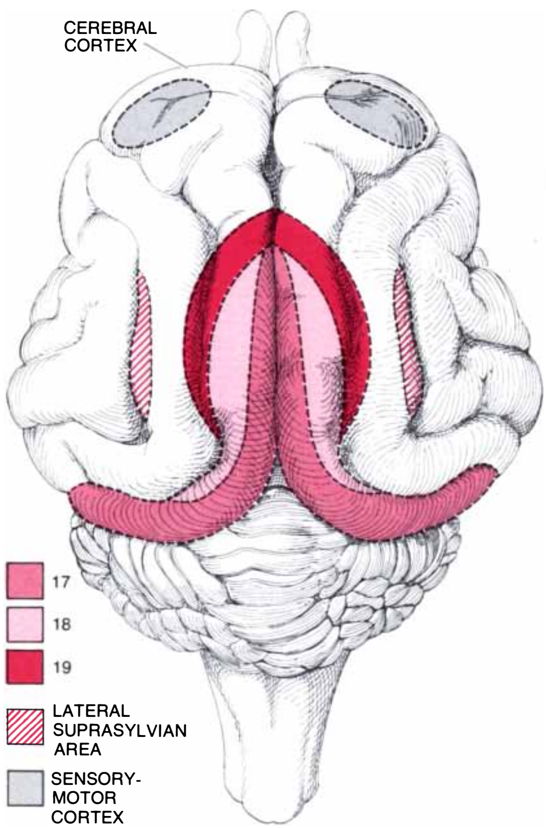
Our first goal, then, was to learn which are the main areas of the visual cortex that project to the pons and which cells their fibers terminate on. Once we had found a group of cells that were receiving visual inputs in the pons we could proceed to examine their function.

A common technique of neuroanatomy is based on the fact that the axon of a nerve cell deteriorates rapidly when the cell body is destroyed. Hence the projection of fibers from one part of the brain to another can be determined by destroying the cell bodies in one region and tracing the degenerating pathways connecting them to the target area. In one series of experiments on anesthetized cats Richard A. King, John F. Stein and we made lesions in those parts of either Area 17 or Area 18 in the visual cortex that receive their input from the center of the visual field. After 10 days the cats were reanesthetized and their brains were removed, fixed and cut into sections. Our histologist, Eileen D. LaBossiere, then stained sections of the pons with Nauta's reduced-silver technique to reveal the location of degenerating fibers projecting from the visual cortex.

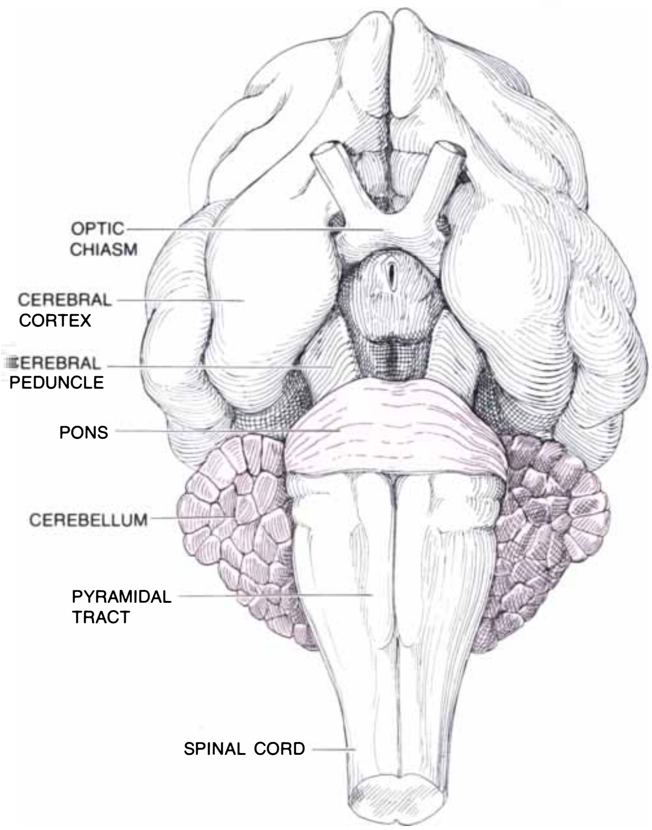
When the lesions were made in Area 18, a clear-cut focus of degenerating fibers appeared among a group of cells in the pons. Lesions in the corresponding part of Area 17, however, caused only negligible degeneration in the pons, suggesting that the two cortical regions might be functionally different. This hypothesis received support when Per Brodal of the Anatomical Institute in Oslo found that the input to the pons from Area 17 was largely limited to those parts of the area receiving information from the periphery of the visual field.

There are two other visual regions in the cerebral cortex of the cat. One of them, Area 19, is continuous with Area 18; the other, the lateral suprasylvian area, is close to the other visual areas but is separated laterally from them. All four regions of the visual cortex receive direct inputs from the eyes by way of the lateral geniculate bodies. James F. Baker, LaBossiere and we undertook a second anatomical study to determine whether Area 19 and the lateral suprasylvian area also send an input to the pons. We found that the projections from Area 19 were light but that the lateral suprasylvian area projects heavily into the same region of the pons that Area 18 does. These two regions of the cortex may thus be specialized for the visual guidance of movement, and they may play a less important role in the visual perception of form.

The findings from degeneration studies have recently been confirmed and enlarged with another anatomical technique. When certain enzymes, for example peroxidase from horseradish, are injected into brain tissue, they are taken up at the far end of axons and are transported back to the cell bodies. If the cell bodies filled with horseradish



TOP VIEW OF THE CAT BRAIN shows the visual and sensory-motor areas of the cerebral cortex. All four visual areas in each hemisphere receive independent representations of half of visual fields.



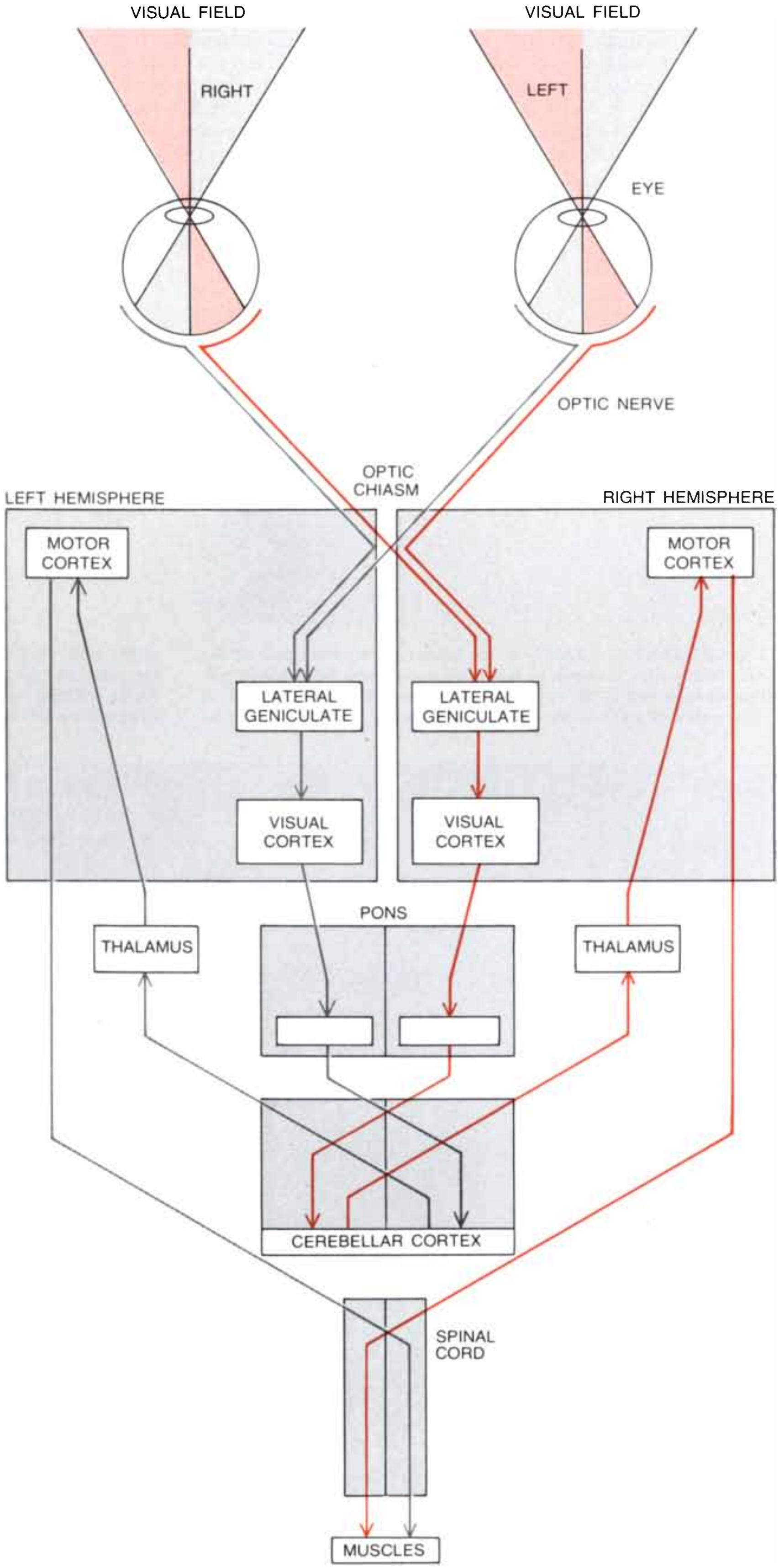
BOTTOM VIEW OF THE CAT BRAIN shows location of pons and cerebellum (*colored areas*). Information from visual cortex travels by way of pons to cerebellum before returning to motor cortex.

peroxidase are then treated with diaminobenzidine, a dark brown reaction product will form, identifying the cells whose axons project to the area where the enzyme was applied. With this technique Baker, George D. Mower and we were able to trace the pathway between the pons and the visual cortex in the opposite direction from the one in which we had traced it by the degeneration technique.

We surgically exposed the bottom surface of the pons in cats and injected a small amount of horseradish peroxidase into its visual area. By approaching the pons from below we were able to avoid the possibility of the enzyme's accidentally leaking into other structures that might also receive fibers from the cortex. When the brains of the cats were later sectioned and examined unstained under the microscope, large pyramidal cells containing the peroxidase reaction product were visible in all areas of the visual cortex except the central portion of Area 17. The labeled cells were confined to a deep layer of the cortex that is known to be a major source of outputs from the cortex to lower brain structures. These cells must be sending visual information to the pons.

Having located a set of cells in the pons that received fibers from cells in the visual cortex, we went on to see if these pontine cells could be physiologically activated by visual stimuli. Since nerve cells transmit information in the form of brief electrochemical impulses, one can detect their responses to sensory input by placing fine recording electrodes near them. Impulses in a given nerve cell or fiber all have about the same amplitude; the effectiveness of the stimulus that gives rise to them is reflected not in amplitude but in the frequency of the "spikes," or impulses, visible on an oscilloscope screen. In general the more spikes per second there are, the more potent the stimulus is.

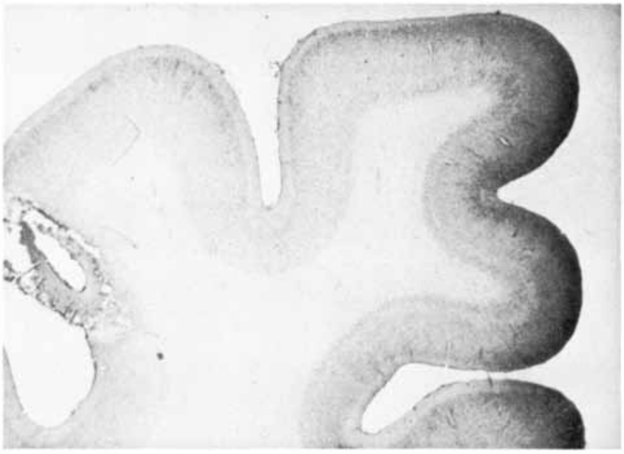
In our physiological experiments Baker, Stein and we recorded the activity of single cells in the pons of cats without lesions and under light anesthesia. The surface of the brain was exposed and tungsten microelectrodes were advanced into the pons with a stereotaxic device, which makes it possible to position the electrodes on three-dimensional coordinates deep in the brain. When the microelectrodes were placed in the region of the pons that receives fibers from the visual cortex, all the cells encountered responded to visual stimulation by increasing their rate of firing. Visually responsive cells could also be activated by electrically stimulating the visual cortex. When we encountered a cell in the pons that could be driven by visual stimuli, and then advanced the microelectrode deeper into the brain, the next cell along the track of the electrode could usually be driven by the same

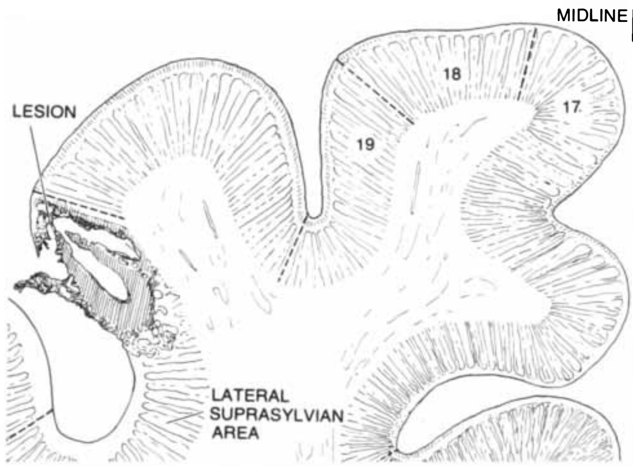


BRAIN PATHWAYS involved in the visual guidance of movement are outlined in this diagram. Information from half of the visual field of each eye flows together at the optic chiasm and travels by way of one of the lateral geniculate bodies to the visual cortex in the opposite hemisphere of the brain. The visual areas on each hemisphere then project to the same side of the pons, but the pathways cross over again in the cerebellum and the spinal cord.

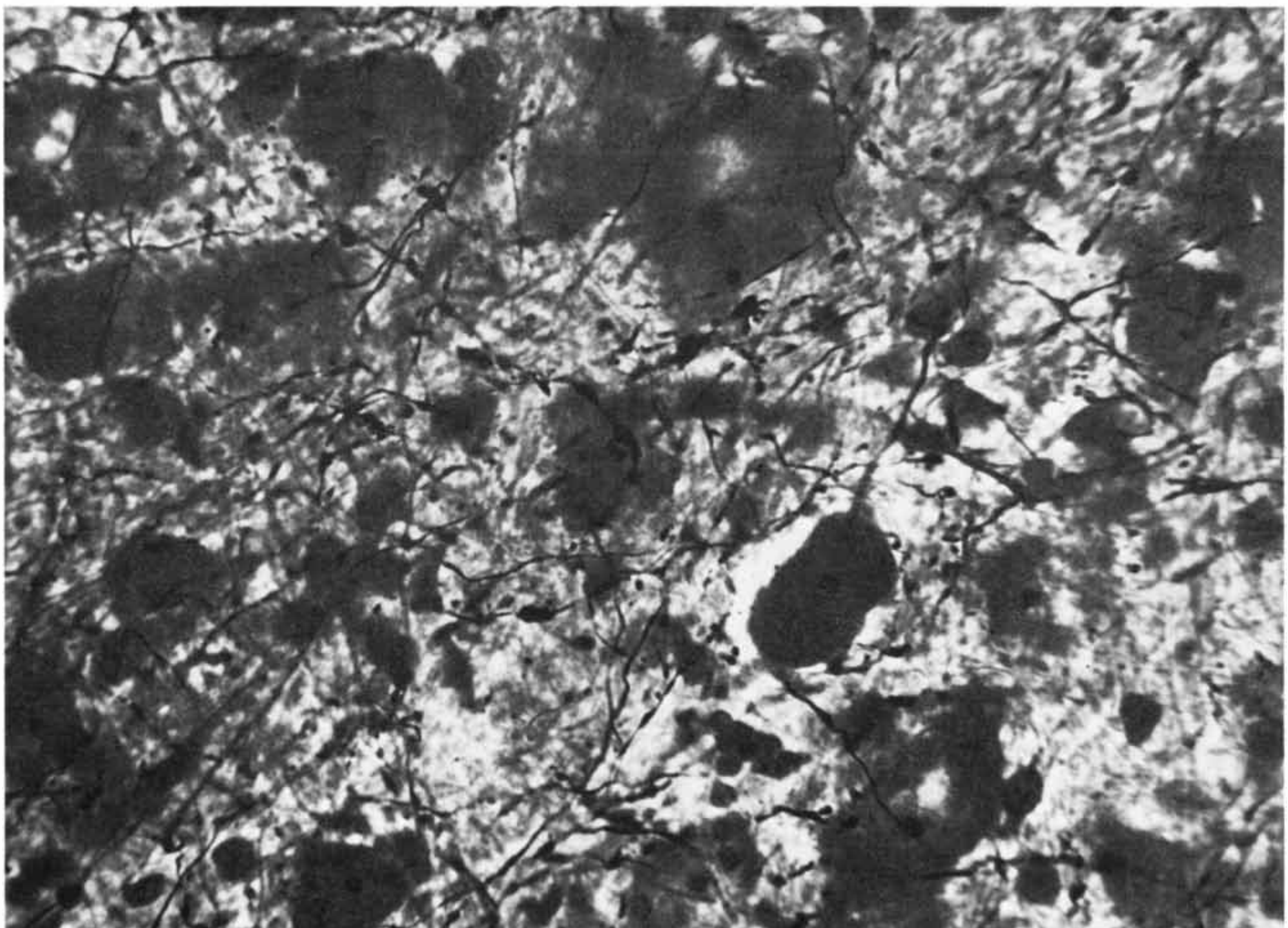
stimuli. Moreover, if the electrode was advanced through the pons at a point immediately adjacent to the preceding track, we usually found visual cells at a similar depth. Cells outside a certain definite area in the pons did not respond at all to the visual stimuli. These observations suggest that visual cells in the pons are located within a specific region that is exclusively visual.

In neighboring parts of the pons we encountered cells that responded to other sensory stimuli, such as clicks or tactile stimulation of the cat's fur or skin. Although we did not study the response properties of these cells in detail, they too were found in distinct clusters. All the pontine cells we have tested so far have responded to only one form of sensory stimulation, be it visual, auditory or tactile; we have not yet found any





EXPERIMENTAL LESION in the lateral suprasylvian area of the cat visual cortex is shown in this photomicrograph of a stained section through half of the cat brain. Such lesions destroy nerve cells in circumscribed areas of the visual cortex, leading to the degeneration of the cells' long fibers, some of which project to the visual cells in the pons. The degenerating fibers can be selectively identified by the Nauta staining technique, so that this method is a powerful tool for tracing the anatomical pathways connecting the cortex and the pons.



DEGENERATING FIBERS of corticopontine cells, the result of lesions in the visual cortex, appear as irregularly fragmented black lines in this photomicrograph of a thin section through the pons. Fibers have been selectively stained black by the Nauta silver technique.

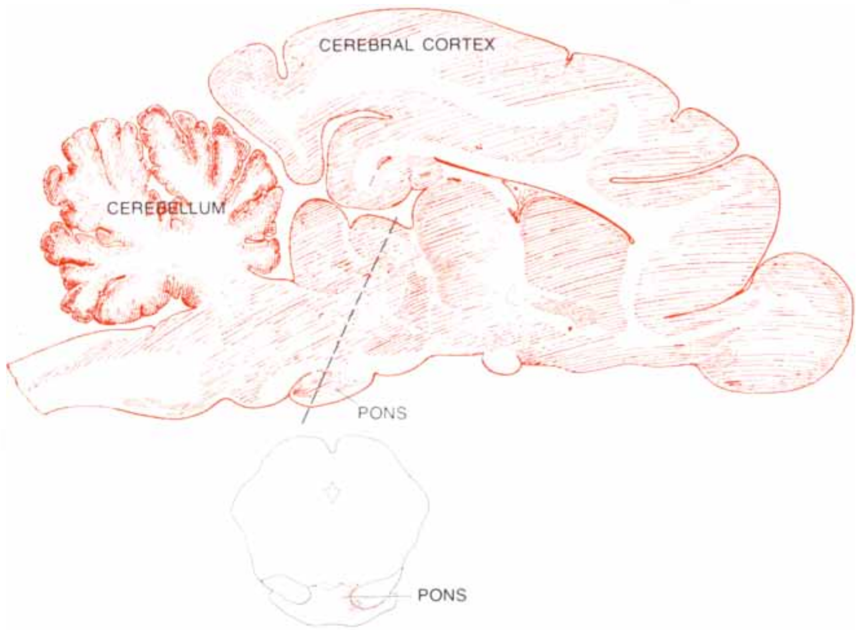
cells that receive convergent information from more than one sense organ.

About half of the pontine visual cells we studied could be activated by a bright flash, although a flash was rarely the best stimulus. The flash response was useful, however, because it enabled us to measure precisely the latency of activation, that is, the time between the flash and the first spike. Knowing this time, we could estimate the shortest pathway by which cells in the pons receive their visual input. Thirteen of the 232 cells we studied were activated in 20 milliseconds or less after a bright flash. This short period of latency allows only enough time for the passage of an impulse through at most a few synapses in the visual cortex on its way to the pons.

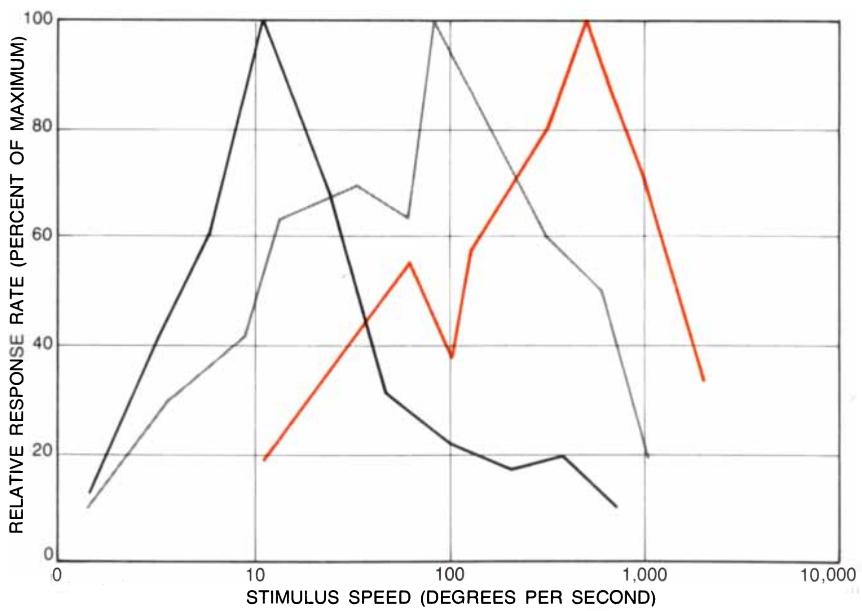
What kind of visual information is relayed by way of the pons to the cerebellum? In order to answer this question we went on to study the receptive fields of visual cells in the pons, that is, the regions of the visual field where visual targets affect the rate at which the visual cells in the pons fire. The receptive fields ranged in size from three by four degrees up to a complete hemifield, half of the visual field, and on the average they were larger than those of cells in the visual cortex. One possible way in which such large receptive fields could be achieved would be if the outputs of several cells in the visual cortex, each with a small and slightly different receptive field, converged on a single cell in the pons.

Although the visual cells in the pons receive their input from the visual cortex, their responses differ markedly from those of the cells in the cortex. Nearly all the pontine cells we tested responded maximally to a particular direction of target motion; in most cases the motion of the target in the opposite direction either failed to drive the cell or actively inhibited it. We studied the motion sensitivity of some cells in detail, varying the speed of the moving target and measuring the effectiveness of different speeds in causing the cell to fire. The pontine cells responded to a broad range of target speeds, from a few angular degrees per second up to more than 1,000 degrees per second, without losing their directional specificity, although there was an optimum speed for each cell. This range of speeds is larger than that of cells in the visual cortex, again suggesting that several cells in the cortex, each with a different preferred speed, might converge on a single cell in the pons.

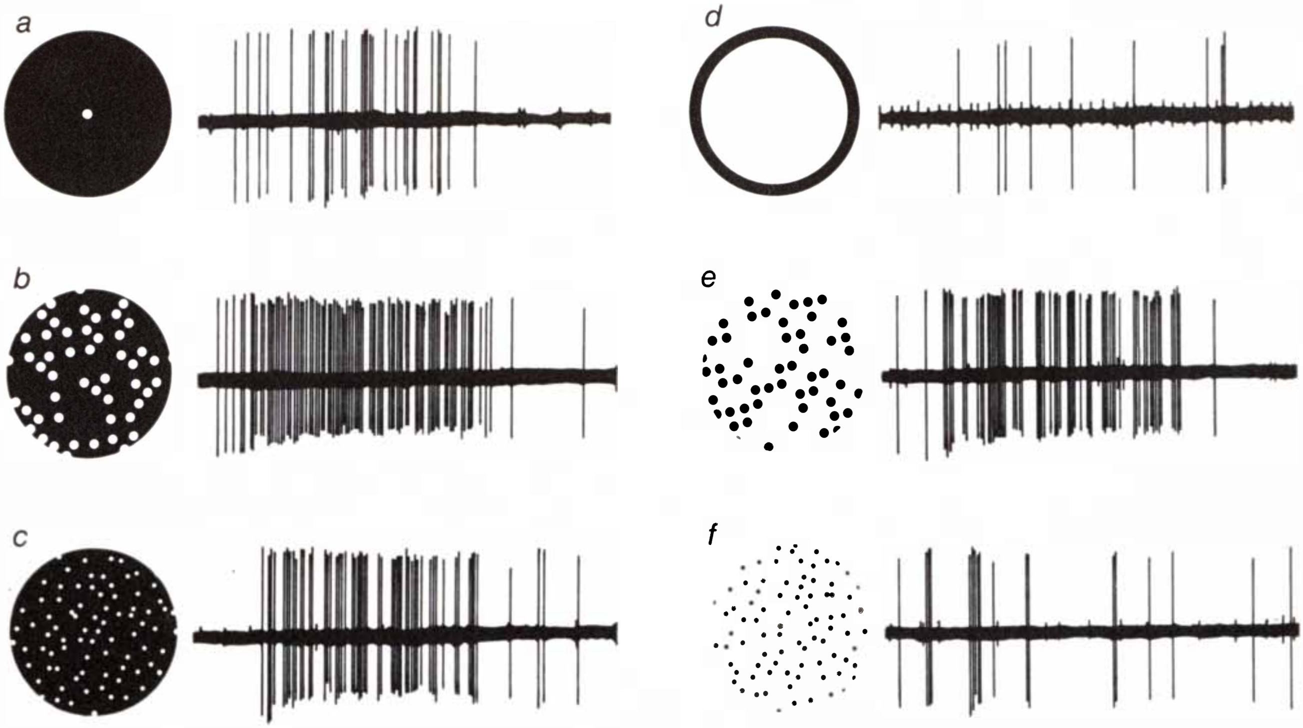
Direction and speed are therefore the major determinants of the firing rate of visual cells in the pons, with the precise shape and orientation of the targets usually being less important. The pontine cells do, however, differ in their preference for targets of different configurations and sizes. Large targets containing many spots were the most effective stimuli for activating about half of the pontine cells we studied. Some cells had a strong preference for such multiple-spot targets; they were not activated at all by a single spot. They would fire in response either to several black spots on a white background or to several white spots on a black one, although the white spots were usually more effective. Other pontine cells were preferentially driven by a single moving spot. There was usually an optimum size for the spot, and large targets often failed to activate the cell at all. For most cells in the pons oriented bars and edges were not more



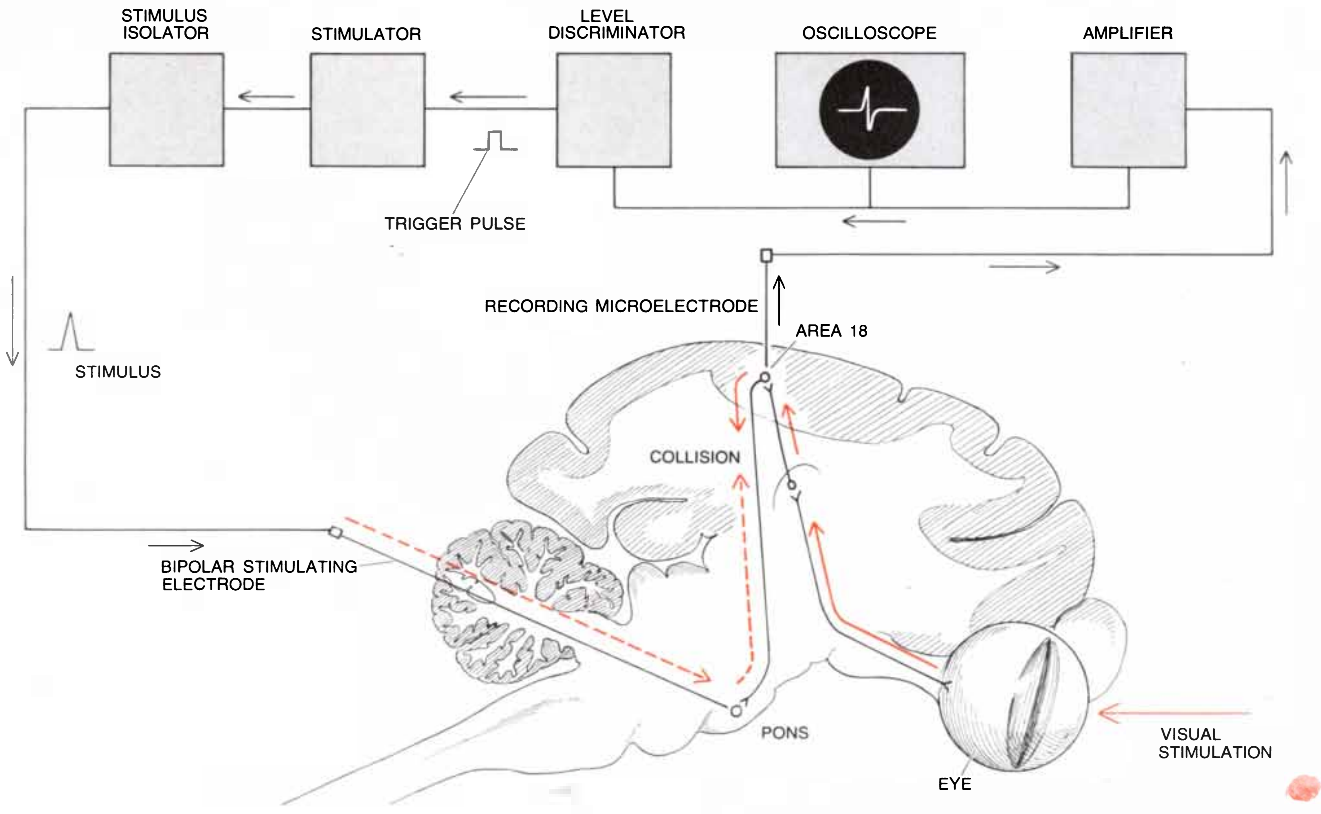
FOCI OF DEGENERATION in the pons produced by experimental lesions in two areas of the cat visual cortex are mapped in this tracing of a cross section of the pons viewed from the front. Black stippling illustrates the area of degeneration following a lesion in Area 18; colored stippling represents degeneration following a lesion in the lateral suprasylvian area of the opposite hemisphere. Visual areas in each hemisphere project to overlapping regions on each side of the pons; for clarity, however, only one area of degeneration is mapped on each side.



RESPONSES TO TARGET SPEED of three visual cells in the pons show that the cells are sensitive to a broad range of speeds of movement, from a few angular degrees per second up to more than 1,000 degrees per second. There is, however, a distinct optimum speed for each cell. Responses were measured with an oscilloscope by counting number of "spikes" per stimulus sweep at each speed and plotting the number as a percentage of cell's maximum firing rate.



RESPONSES TO VISUAL TARGETS of a particular cell in the pons demonstrate the remarkable specificity of these cells for different target configurations. The responsiveness of the cell to each visual stimulus was determined by presenting the target in the visual field and recording the cell's firing pattern with a microelectrode connected to an oscilloscope. All six targets evoked a response, but most effective stimulus for this particular cell was a pattern of white dots on a black background that was moving in a specific direction (*b*).



ANTIDROMIC-INVASION EXPERIMENT identifies cells in the visual cortex that send fibers to the pons by electrically stimulating nerve endings in the visual area of the pons and detecting impulses conducted antidromically, or "backward," up the fibers to the cell bodies in the cortex. To ensure that the fiber and cell body are parts of the same cell without an intervening synaptic relay, the cell being recorded from can be induced to fire by visual input. This signal is then amplified and used to trigger the stimulator, which initiates an antidromic impulse at the nerve ending. If the stimulated cell and the visually driven cell are one and the same, the two impulses will collide midway along the fiber, and the antidromic nerve impulse will never reach the cell body and will not appear on oscilloscope screen.

effective stimuli than spots, and often they were less so. This behavior is in contrast to that of most cells in the cortex, which respond strongly to oriented edges but weakly to spots.

The response properties of the visual cells in the pons tell us something about the kind of information that is relayed from the visual cortex to the cerebellum. What naturally occurring stimuli might activate these cells? The cells responding preferentially to a single moving spot could be specialized for following the rate and direction of movement of a single object, which in the case of the cat might be a small running animal. Those responding to the movement of large textured fields commonly prefer movement away from the vertical meridian and downward, and thus they could be responsible for detecting the direction of the ground as seen by a walking or running animal.

Since the behavior of the visual cells in the pons differed so much from the previously reported behavior of visual cells in the cortex, we decided to study how information is processed in the cortex to give rise to the very different kind of responses that occur in pontine cells. To approach this problem Baker, Mower and we turned to a technique known as antidromic invasion. The technique calls for electrically stimulating the axons of corticopontine cells (cells in the cortex that project to cells in the pons) at their far end, so that a spike is conducted along the fiber and invades the cell body. The conduction of the nerve impulse from the end of the axon to the cell body is antidromic, that is, in a direction opposite to the usual one. If a microelectrode is placed so that it records nerve impulses at the cell body, one can see a spike arrive a few milliseconds after each stimulus pulse is administered to the cell's axon. (The exact amount of delay depends on the length and diameter of the axon.) With this technique it is possible to learn whether a cell in the visual cortex has an axon that projects to the pons, and if it does, to study the properties of that cell.

Only a small percentage of the millions of cells in the visual cortex send their axons to a given structure in the pons, so that finding corticopontine cells is not easy. To increase our chances of success we simultaneously recorded with four electrodes in the cortex and switched among them with each stimulus pulse; the stimulating electrode was also an array of four electrodes placed in the visual area of the pons. So far we have recorded from 57 well-isolated corticopontine cells.

There are two ways electrical stimulation of the pons might cause a cortical cell to fire: directly, through an antidromic impulse conducted up the cell's axon, or indirectly, by exciting an intermediary cell that acts as a synaptic relay to the cell being recorded from. In order to differentiate between these two possibilities we tested each cell for "collision." This is done by making the cell fire in response to a visual stimulus (such as a multispot target) and then amplifying the elicited spike and using it to trigger the electrical stimulator, which in turn drives an antidromic spike up the cell's axon. The external electrical circuit operates almost instantaneously, so that if the visually driven cell body and the electrically driven axon are parts of the same neuron, the antidromic spike traveling up the axon from the stimulating electrode will meet the visually elicited spike traveling down the axon. When this happens, the two impulses will "collide" and disappear, because a length of axon behind each impulse is temporarily unable to conduct. The antidromic spike will therefore fail to reach the cell body and will not appear on the oscilloscope screen. If, on the other hand, the stimulator is driving the cell indirectly through a synaptic relay, there will be no collision, and the elicited spike will appear on the oscilloscope screen.

A surprising finding that has resulted from the antidromic-invasion experiments is that the corticopontine cells comprise a subset of cortical cells behaving more like pontine cells than like other cortical cells. Much of the convergence needed to produce the large receptive fields and broad speed ranges typical of visual cells in the pons hence appears to be occurring in the cortex. One property in which corticopontine and pontine cells differ is that the corticopontine cells are more sensitive to the orientation of line stimuli. A given cell's orientation preference for an oriented line stimulus, however, does not correlate with its direction preference for a moving spot pattern. It may be that many of these cells converge onto a single cell in the pons in such a way that directional specificity is preserved even though sharp orientation preference is lost.

In sum, the movement of an image across the retina is necessary to activate a visual cell in the pons, but such cells are not highly selective for stimuli of a definite orientation or shape. This suggests that the analysis of visual features is accomplished by other brain pathways. The motion of objects in the view of a stationary cat and the movement of the ground past a walking or running cat each activate a different class of cells in the pons. These cells in turn send impulses to the cerebellum, which also registers the position and velocity of every muscle and joint. The cerebellum then combines these two kinds of information to control the position of the body and the limbs in an actively moving animal.

The Forming of Sheet Metal

How a metal behaves when it is stamped is a matter of large practical importance. Modern knowledge of the solid state is making the process less of an art and more of a science

by S. S. Hecker and A. K. Ghosh

A visitor to a factory where sheet metal is being formed, with presses rapidly stamping out identical parts from metal blanks, might well think he is witnessing an advanced technology in action. Actually the forming of sheet metal is more of an advanced art. The industry relies heavily on the judgment and experience of master craftsmen. Only recently have advances in analysis and in knowledge of the atomic structure of metals begun to fortify the art with science, putting the technology on a firmer footing and pointing the way to better performance and lower cost for the thousands of metal parts that are made daily on a mass-production basis.

Although sheet metal was worked for thousands of years in the production of coins, utensils and objects of art, it was only a century ago that the process was mechanized and began to resemble the metal-stamping lines of today. The mechanization of sheet forming was in turn a major step toward mass production. Today the forming of sheet metal touches the life of almost everyone as stamping machines produce a vast variety of parts ranging from eyelets for shoes to fenders for automobiles. The industry is a major component in the economy of every modern industrialized country.

Early in the 16th century a French inventor who appears in the annals of metalworking only as Bruiler developed a technique for rolling metal to a uniform thickness. The development made it possible to form metal parts by stamping flat pieces of metal between dies. Nevertheless, iron and steel continued for 300 years to be shaped predominantly by rolling, forging, casting and drawing, because the presses employed to stamp parts were hand-powered until the German engineers Ludwig Keserstein and Johann Luber developed the first water-driven press about 1800. When the American inventor Elisha Root introduced the first crank-powered drop press about 1850, the way was opened for a revolution in manufacturing techniques.

The rise of mass production in the second half of the 19th century was a particular stimulus to the development of sheet-metal forming, which in turn made mass production feasible. Sheet-metal parts offered several advantages over cast and forged ones, including lower weight, greater interchangeability and lower cost. About 1850 the practice of stamping tin-plated sheets of iron or steel to form food containers laid the foundation of the sheet-metalworking industry as it is known today.

Although metal stamping was well established by 1900, the main growth of the industry came when mass production became a feature of the automobile industry. Another impetus was provided by the rapid expansion of the home-appliance industry after World War I with such items as vacuum cleaners, washing machines, refrigerators and toasters. All these developments created a large requirement for sheet metal. The requirement was met by low-carbon steel, which offered the advantages of uniform thickness, good surface finish and again low cost. Low-carbon steel quickly became the universal sheet material, and it retains that role today.

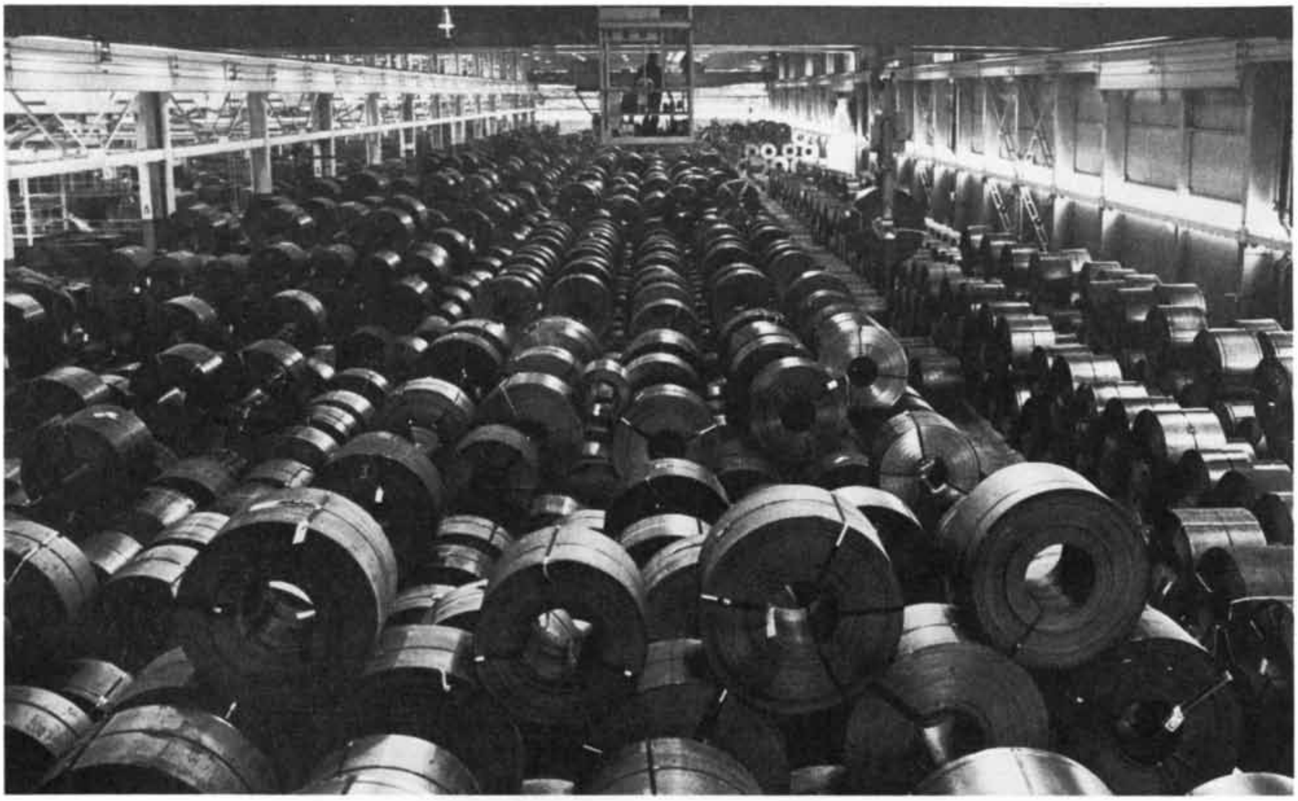
Stamping is by no means the only method of forming parts from sheet metal, but it is economically the most important one, and so we shall focus our discussion on it. In the commonest form of stamping, a precut metal blank is formed in a mechanical press between a set of dies that have been carefully shaped to yield the desired part. The process begins with a blanking operation in which the sheet metal, which is stored in coils (some weighing as much as 30 tons), is automatically unrolled and cut to the proper size by shearing dies. The proper size is usually somewhat larger than the finished part because of the need for edges that can be held tightly while the blank is stamped. After stamping, the edges are trimmed off. On a large stamping the trim loss can be as much as 30 percent; the trimmed metal can only be sold as scrap for a fraction of its cost.

The next step is usually flanging, which is essentially a bending operation. A flange is ordinarily needed if the part is designed to be attached to another part, as a fender is attached to the body of an automobile. After flanging, the part may be stamped a second time in a different set of dies; this step is sometimes needed to sharpen contours and corners that do not attain their specified dimensions in the first stamping.

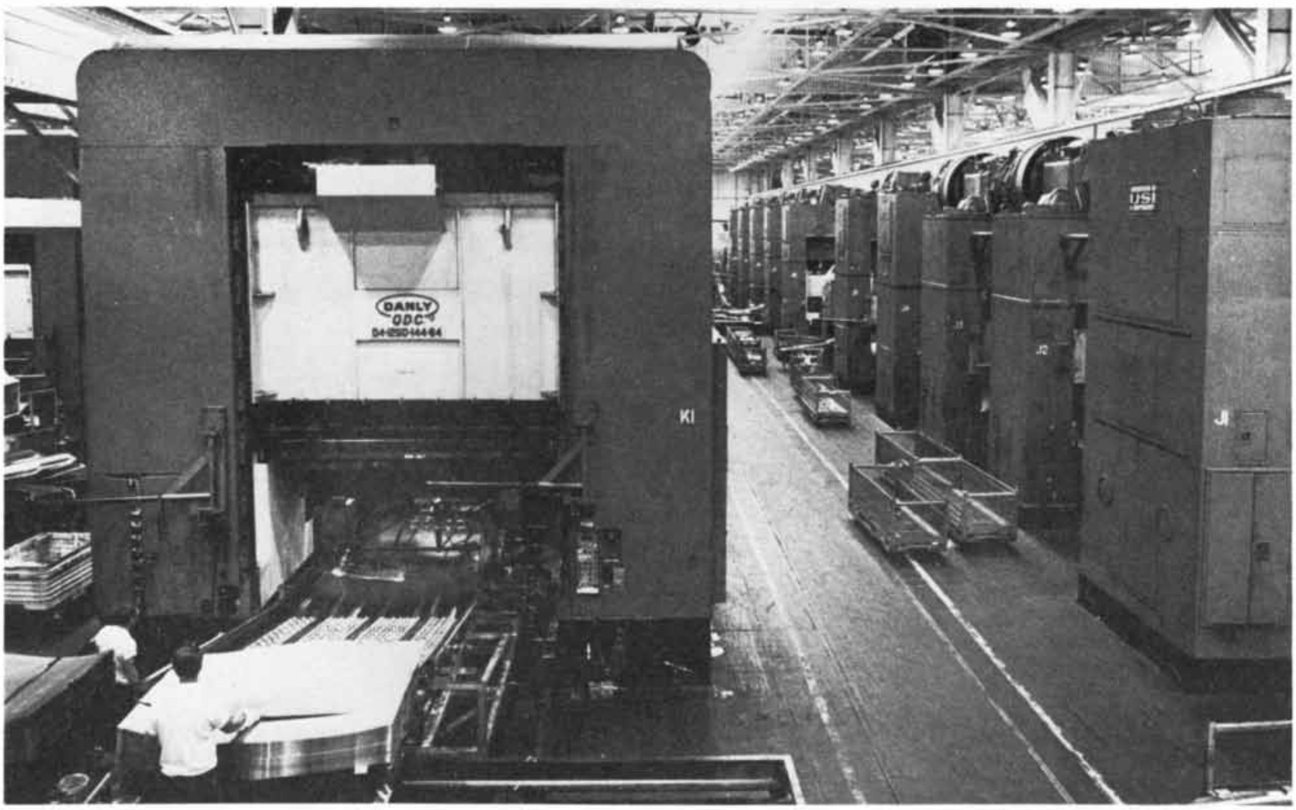
A typical stamping plant employs a variety of dies and presses. The pressing force can be applied by a hydraulic system or a mechanical one, with mechanical systems being generally favored because they are faster. Double-action presses that involve the motion of two rams, one for the blank holder and one for the main die, are commonest. The modern stamping line is highly or fully automatic, with mechanical fingers for feeding and transferring parts, lubricant sprayers synchronized with the motion of the press, conveyor systems based on magnetic or vacuum devices, photocells that actuate the drive systems and an inspection system that functions without stopping the production line for the removal of a part. As a result extremely high rates of production (for example 100,000 oil-filter cans per day from a single plant) can be achieved.

Automatic stamping lines were in operation long before anyone understood what kind of flow takes place in a piece of metal as it is being stamped. That knowledge is quite recent. The processes involved are drawing and (usually) stretching. One can follow them by visualizing a press that is about to stamp a metal blank. Above the blank are the main ram, which carries the punch, and the blank holder, which clamps down the edges of the blank. Below the blank is the main die.

The first action of the press pushes down the blank holder, causing the



COILS OF SHEET METAL that will be formed into parts for automobiles are stored at a plant of the General Motors Corporation. The metal is low-carbon steel. Coils are transported to an adjacent stamping room, which appears in the photograph at the bottom of the page. There they are uncoiled and cut into blanks of appropriate size, which are fed into large presses that stamp out the parts.



STAMPING PRESS forms a door panel in the General Motors plant. The metal is handled automatically once the operator in the left foreground has fed the blanks individually onto the rollers that pull them into the press. The machines at the right also stamp parts.

blank to be held fast at its edges. The second action pushes down the main ram with its punch. The metal is wrapped around the punch as the punch descends into the die cavity. Essentially the metal is drawn, or pulled, from the edges into the cavity.

Since the blank is forced to contract circumferentially as it is drawn radially inward, it tends to buckle or wrinkle. A proper flow of the metal, counteracting this tendency, is achieved by inclining the punch and die assembly, by applying heavy pressure with the holder and (sometimes) by having draw beads on the surface of the die below the blank holder. A die may incorporate several of these rodlike beads, each with a diameter of from half to three-quarters of an inch. They control the flow of metal by forcing the sheet to bend and unbend as it passes over the beads before entering the die cavity.

Unless the part being formed has a very simple shape, portions of the blank are not only drawn but also stretched as the blank is pressed into the die cavity by the punch. Stretching is defined as an extension of the surface of the sheet in all directions. The material requirements for drawing and stretching differ considerably. Progress toward understanding the influence of material properties on the flow of metal has been made chiefly through laboratory tests that treat drawing and stretching separately.

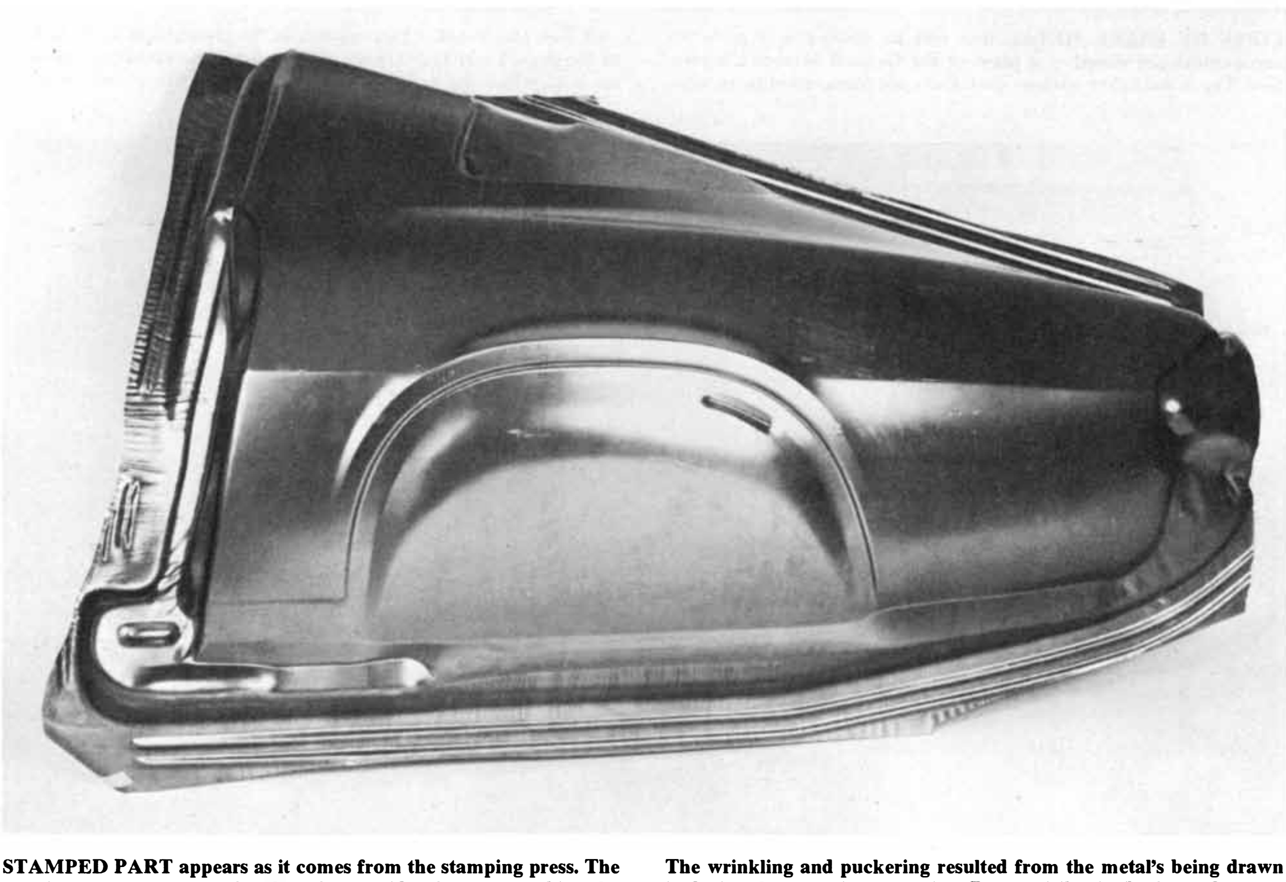
The events in drawing can be demonstrated by depicting the formation of a cylindrical cup with a flat bottom [*see bottom illustration on opposite page*]. The process is often called deep drawing. Most of the deformation in deep drawing occurs in the flange; very little takes place in the part of the blank that touches the punch. The process causes little change in the final thickness or surface area.

Circumferential contraction in the flange will cause wrinkling unless sufficient hold-down pressure is applied. The load required to deform the flange is transmitted from the bottom of the cup to the flange by way of the cup wall. If this load goes beyond what the wall can support, the metal tears near the bottom of the cup.

Thus for good drawing one needs a material that resists thinning in the cup wall. In other words, the material should have less strength (so that it will deform more easily) in the plane of the sheet than in the thickness. This directional differential in strength is termed plastic anisotropy. The property is easily measured by a simple test in the laboratory. A long, thin strip is cut from the sheet and stretched. The plastic anisotropy is determined by comparing the contraction of the sheet in width and in thickness. If the width contracts more than the thickness, the metal will resist thinning in the course of drawing and so will make deeper cups.

Plastic anisotropy is developed during primary metalworking, such as in rolling, and reflects the crystalline nature of metals. A metal consists of innumerable small grains, or crystals, all bonded together in different orientations. In each crystalline grain the atoms are arranged in a highly regular three-dimensional lattice. The crystallinity is the result of the atomic binding peculiar to metals, which favors highly symmetrical and closely packed structures.

Closely packed crystal structures strongly resist forces that tend to change their volume, but they can easily shear



STAMPED PART appears as it comes from the stamping press. The part is a "quarter panel" for the left rear side of an automobile; the arched area at the center, which will be over the wheel, will be removed in a trimming operation, as will much of material around the edges and at the right end, where the tail light will be. The material at the edges was for holding the blank in the press as it was stamped. The wrinkling and puckering resulted from the metal's being drawn in during the stamping operation. Barely visible in the formed corner above the wheel area is a dark rectangle; it is made up of a grid of circles that was put on the blank so that the deformation caused by the stamping could be studied. Two photographs showing how the circle-grid method reveals details of deformation appear on page 108.

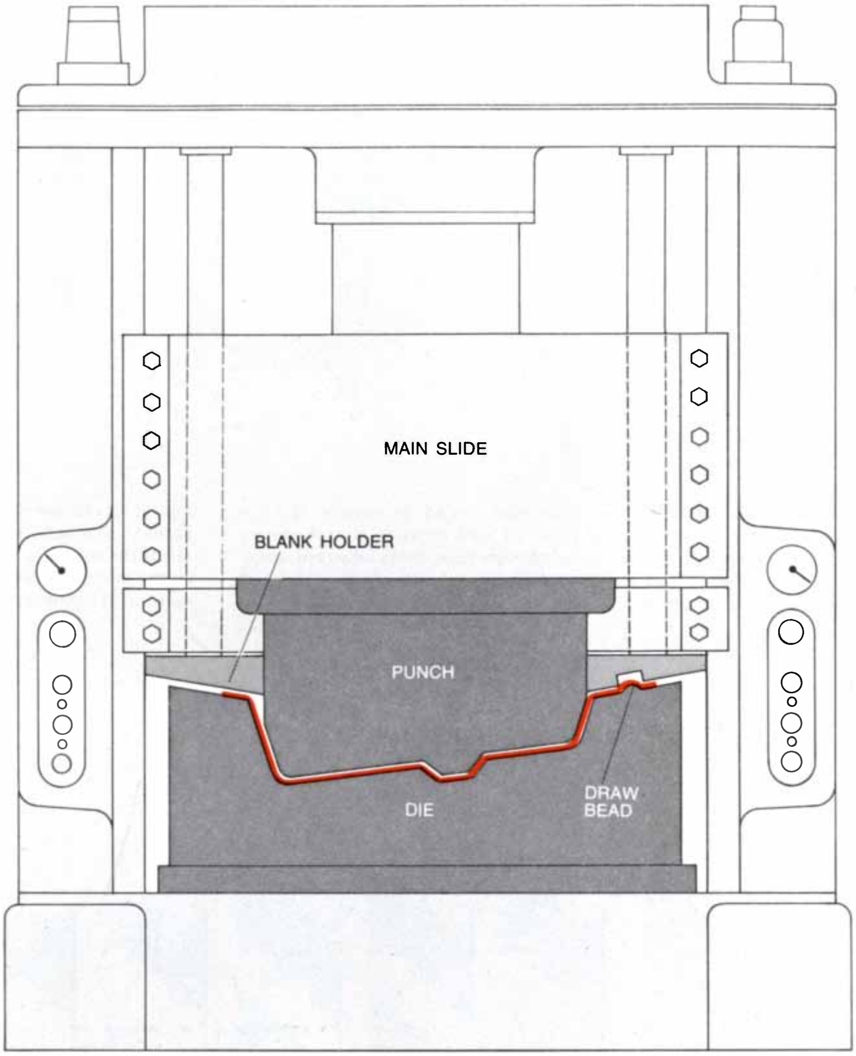
and change shape when layers of atoms slip over one another. The layers slip most easily along closely packed crystal planes in closely packed directions. Simple crystal structures have a high degree of symmetry and hence many closely packed planes and directions, so that plastic flow is easy.

Slip is made still easier by the crystalline imperfections called dislocations. They are small departures from the regular arrangement of the atoms in a grain, and they enable atoms to slip in tiny steps instead of in entire rows at a time. Indeed, the motion of dislocations is the only mechanism for slip. In the simple crystalline structure of many metals such dislocations are easily introduced; they move freely and they multiply readily during deformation, and so they account for the high ductility of such metals.

During the enormous reductions (as large as 1,000 to one) involved in rolling sheets for automobile bodies from steel ingots the individual metal grains line up in certain preferred directions. The properties of crystals vary with direction, because of the directional regularity with which their atoms are stacked, and the bulk properties of the sheet take on a similar directionality. For the best resistance to thinning, and hence the best property for drawing, as many crystals as possible should be aligned so that the direction in which they are strongest is parallel to the direction of the thickness of the material.

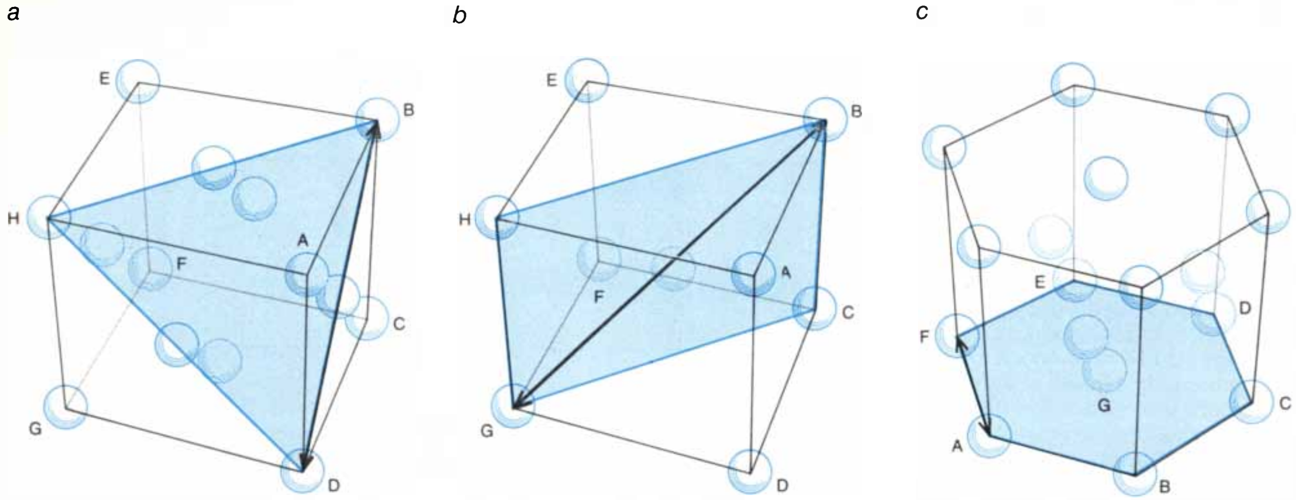
In crystals with a cubic symmetry, which is common in metals, this direction is along the body diagonal of the cube. In metals such as steel, which has a body-centered-cubic crystal lattice (an atom at each corner of the cube and one in its center), the preferred alignment of crystals can be achieved fairly easily. In metals such as copper, brass and aluminum, which have a face-centered-cubic lattice (an atom at each corner and one at the center of each face of the cube), the alignment is difficult to achieve because of the multiplicity of directions in which crystals can slip during deformation. In metals with other crystal structures the direction of slip is highly limited, and so the opportunity of obtaining directionality exists, although it does not necessarily give rise to a favorable alignment. For example, both titanium and zinc have a hexagonal-close-packed crystal structure, but in titanium the alignment is favorable for deep drawing whereas in zinc it is not.

The importance of plastic anisotropy in deep drawing has been recognized only in the past 15 years. Before that the trait was considered undesirable; a metal that did not deform in the same way in all directions was thought to be difficult to shape. Steel producers have made great progress in developing deep-draw-

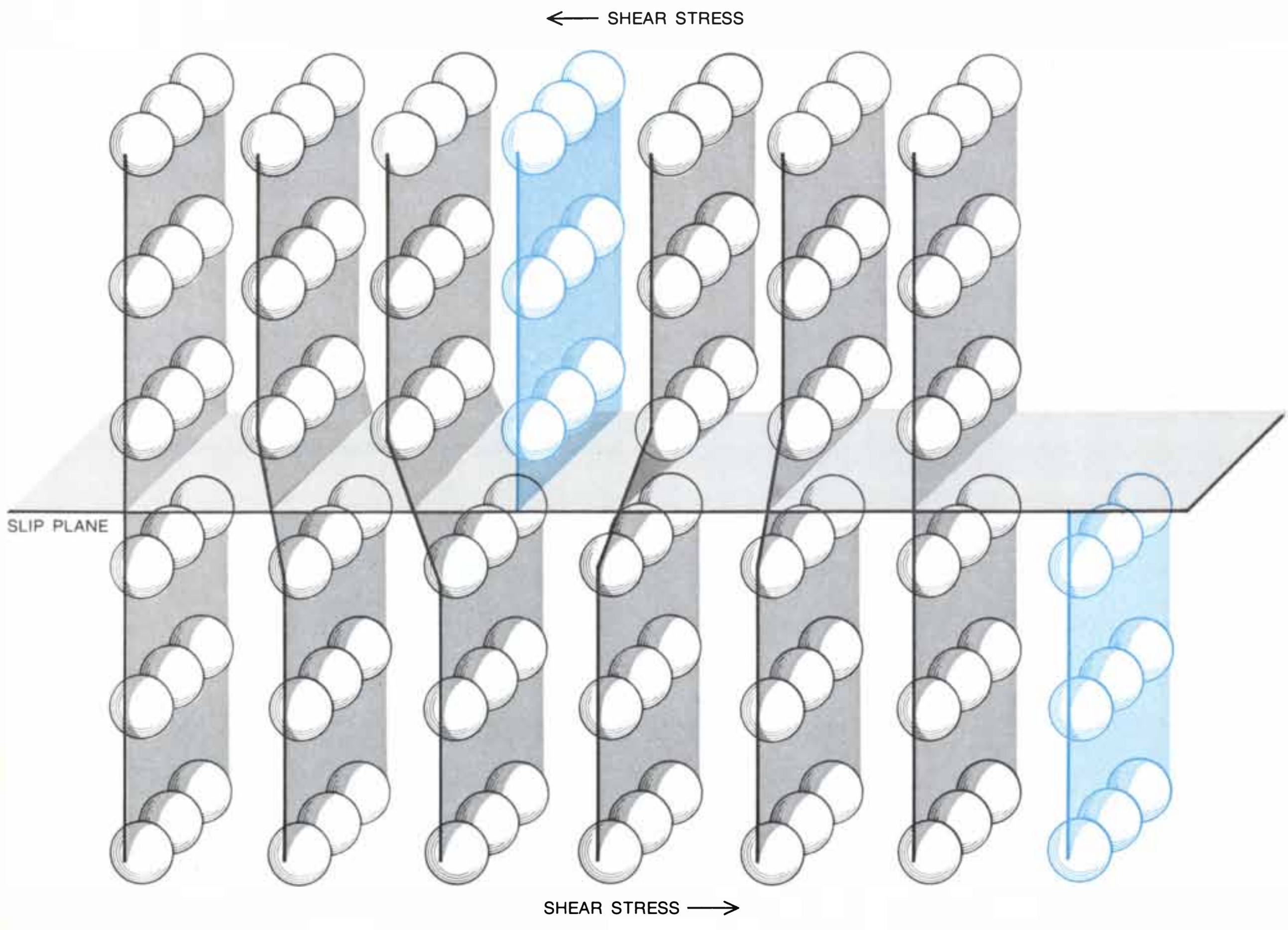


STAMPING OF PART in a double-action mechanical press is depicted. The double action involves the motion of two rams: the main slide, which holds the punch, or upper die, and the ram that constitutes the blank holder. The first action of the press pushes down the blank holder, which clamps the precut blank around its edges. The next action pushes down the main slide, so that the part (*color*) is formed between the punch and the lower die. Draw bead helps to control the flow of the metal by making it bend and unbend on the way into the die cavity.

DRAWING, one of the two major modes of forming metal by stamping, is illustrated by the deep drawing of a cylindrical cup. The circular blank is drawn into the cup-shaped die by the flat-headed punch. The wall of the cup supports the major part of the load and tends to undergo thinning. Best material for drawing is therefore a material that is resistant to thinning.



CRYSTAL STRUCTURES commonly found in metals are depicted. They are face-centered cubic (*a*), with an atom at each corner of the cube and one at the center of each face; body-centered cubic (*b*), with an atom at each corner and one in the center of the cube, and hexagonal close-packed (*c*). The structure affects the ability of a crystal to change shape by the mechanism of slip, or change in the position of atoms, and so is an important consideration in choosing a metal for forming. Slip is easiest along closely packed planes (*color*) in the most closely packed directions (*arrows*). Equivalent planes, such as HFD in *a*, are also favorable to change of shape by slip.



ROLE OF DISLOCATIONS in the mechanism of slip is portrayed. The dislocation shown is an extra half plane of atoms (*dark color*) in the crystal lattice. Deformation occurs by shearing along a slip plane that is perpendicular to the extra half plane of atoms. If shear stress is applied as indicated by the black arrows at the top and bottom, atoms are displaced in a movement that resembles the shifting of a wrinkle in a rug, resulting in a change of shape of the crystal as is suggested here by the half plane of atoms portrayed in the light color.

ing steels; titanium producers have also taken advantage of preferred anisotropy. Face-centered-cubic metals, however, still perform poorly in drawing operations.

During stretching, as opposed to drawing, all loads are tensile. There is no beneficial squeezing action. The property a metal needs most in order to stretch well is the ability to become stronger while it is being strained, or deformed. It is this intrinsic hardening process, which is known as strain hardening, that makes it progressively more difficult to bend a wire when the wire is being bent repeatedly (until, of course, the wire breaks). Strain hardening helps to prevent the localization of strain by causing the deformation to shift to less deformed areas. Hence the process facilitates a more uniform deformation.

Strain hardening in metals is best demonstrated in a tensile test. A long strip of metal is pulled in one direction as the load required to pull the strip and the extension that results are measured and recorded. The load required to extend the metal continues to increase even after the point where permanent deformation begins. The greater the increase in load with extension, the greater the strain hardening.

With stretching the metal becomes steadily thinner and thus loses its ability to carry a load. This geometric weakening competes against strain hardening and eventually dominates it. At the point where the two are in balance the load reaches a maximum. Thereafter deformation becomes unstable because it continues with ever decreasing loads. It gradually concentrates around a weak spot in the material, a process termed diffuse necking. Eventually the deformation becomes totally localized in a neck (a "thickness trough") and the metal tears.

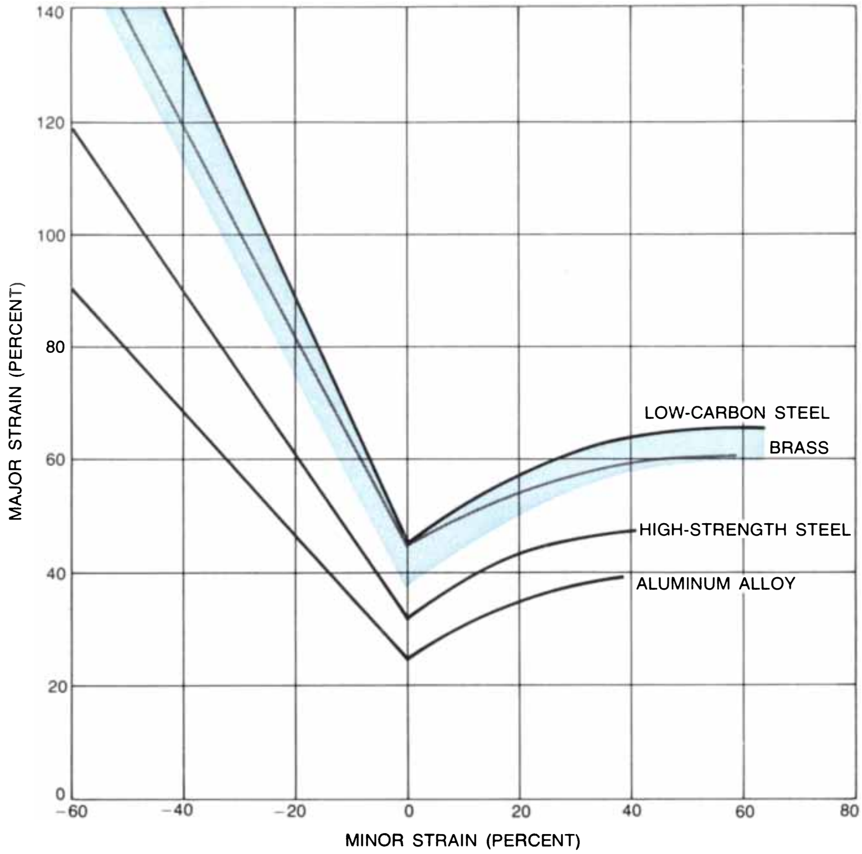
Once diffuse necking begins, a gradient in the rate of deformation also develops along the length of the specimen. The strength of many metals is sensitive to the rate of deformation. During necking a metal that hardens as the rate is increased ("strain-rate hardening") will resist the localization of deformation and delay the onset of local thinning. Both strain hardening and strain-rate hardening are influenced by the temperature of deformation. When a sheet of metal is being shaped by dies, gradients in deformation and the rate of deformation build up quickly because of the complex geometry of the shape and the friction resulting from the contact between the metal and the punch. Both strain hardening and strain-rate hardening are therefore vital in promoting a uniform deformation.

Strain hardening and strain-rate hardening can be explained in terms of the behavior of atoms during the deformation of metal. A change of shape requires slip within the metal crystals. Slip results from the motion of dislocations. Hardening depends on how much resistance dislocations experience as they glide through a crystal. Resistance is due to obstacles such as crystal boundaries, foreign atoms and faults in the stacking of the atoms in the crystal. The amount of resistance depends on the type of crystal structure. In brass, bronze and certain stainless steels, for example, stacking faults extend over distances equivalent to many atomic diameters; the faults therefore can be very strong obstacles, so that the metal resists the cross-glide of dislocations from one slip plane to another. As a result the dislocations start piling up in two-dimensional arrays, much like automobiles at a traffic light, and their continued packing leads to rapid hardening. At the other extreme of hardening behavior aluminum and iron exhibit ease of cross-gliding and so harden at a lower rate.

Obstacles can give rise to either local or long-range disturbances in a crystal. If the disturbance is long-range (perhaps greater than 10 atomic diameters), such as large foreign particles or piled-up dislocations on parallel slip planes in brass, the rate of deformation will not influence plastic flow or hardening. If the disturbance is local, such as the discontinuity due to foreign atoms or other individual dislocations, the thermal vibrations of the atoms in the crystal lattice can assist in the plastic flow. If the rate of deformation is high, there is little assistance, and the result is greater hardening than takes place at low rates.

The importance of these microscopic processes of strain hardening and strain-rate hardening in the uniformity of large-scale deformation is best assessed in the laboratory with a punch-stretch test. A metal blank is marked with a precise grid of circles of small diameter, which provide a means of measuring deformation. It is then clamped firmly to avoid any drawing in at the edges and is deformed over an unlubricated hemispherical steel punch. For good stretchability the property desired is uniform deformation over the punch.

Another important factor in stretching is the total strain the material experiences before it fails, or tears. Stuart P.



FORMING-LIMIT DIAGRAM, obtained by deforming metals in tests, indicates whether a metal can be shaped without risk of failure, or tearing. The broad colored band represents steel; under strains in the region below the band steel can be expected to undergo forming successfully, whereas above the band the strains probably will cause the metal to fail during forming. The curves for other metals are less firmly established by experience than the steel curve is.

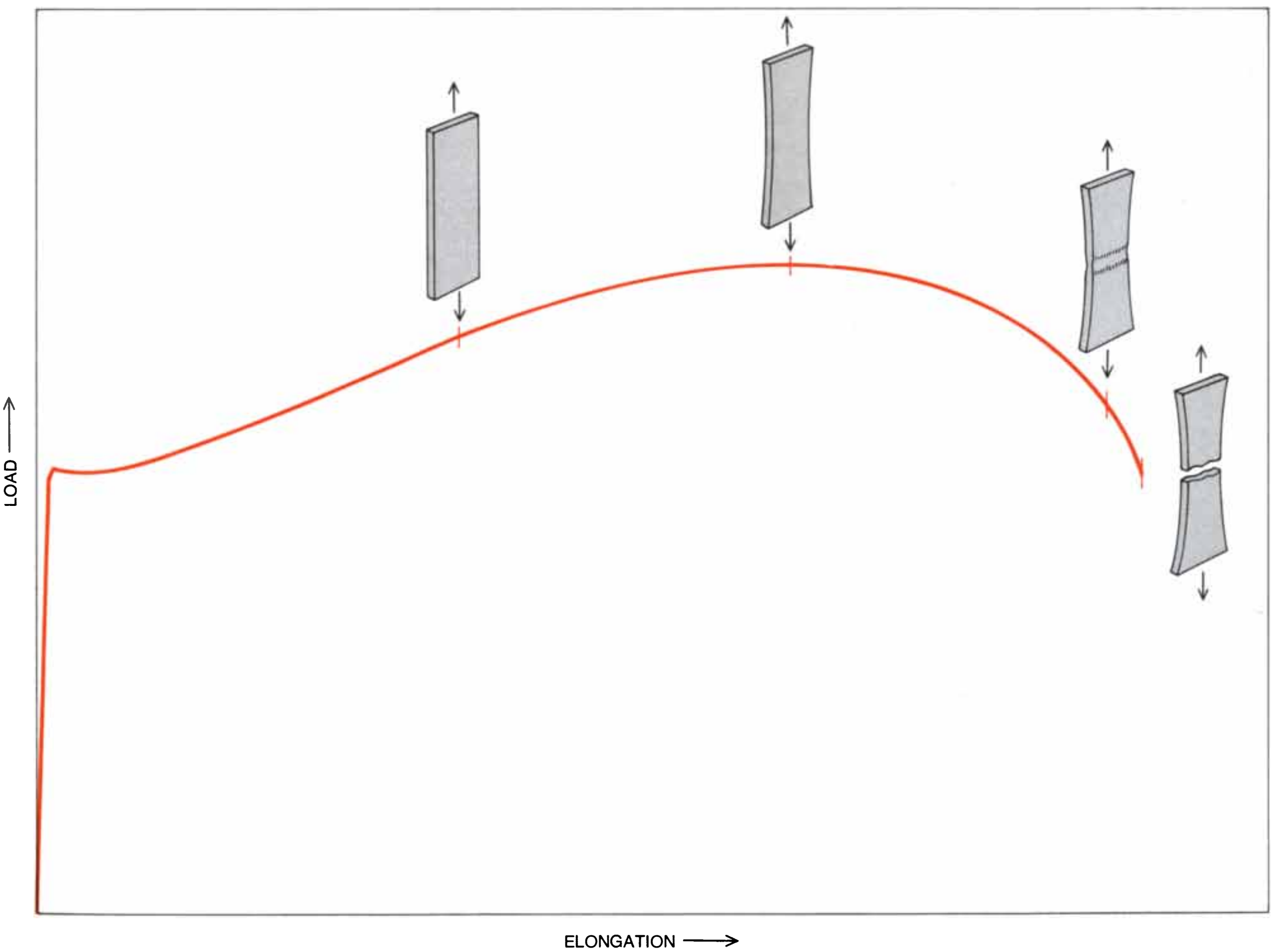
Keeler of the National Steel Corporation and Gorton M. Goodwin of the Chrysler Corporation have developed the concept of an empirical forming-limit diagram. By making many tests in the laboratory and examining hundreds of stampings from the production line they found that there is a unique failure band in the diagram for low-carbon steels. The band is determined by plotting the largest surface strain in the sheet (the major strain) against the strain perpendicular to it (the minor strain). The failure band then separates the combinations of strains that are acceptable (below the band) from the ones that cause failure (above the band). Such curves can now be determined entirely from measurements made in punch-stretch tests. For most stamping operations forming-limit diagrams have given excellent predictions of failure and have become highly useful in predicting stretchability [*see illustration on preceding page*].

The best measure of stretchability is given by the greatest height a dome achieves before failure during the punch-stretch test. The measure combines the importance of strain uniformity and strain to failure and reveals the superiority of brass (high strain hardening) and steel (moderately high strain hardening and strain-rate hardening) and the poor performance of certain alloys of aluminum (moderate strain hardening but strain-rate softening).

The properties of the material are not the only important factor in forming; another one is lubrication. Although little is known about the mechanisms of lubrication in the forming of sheet metal, the beneficial effects are well documented. Lubrication always helps to distribute strain more uniformly. Indeed, it is often more effective than an improvement in the properties of the material.

Bending operations are an integral part of all complex stampings. In bending, in contrast to most stretching operations, there is a severe gradient of stress throughout the thickness of the material. On the outside of the bend the stress is tension; on the inside it is either compression or a reduced level of tension. The severity of the tensile strains depends on the bend's radius, angle and length. Failure occurs on the tensile side by thinning and fracture. Strain hardening, strain-rate hardening and strain to fracture are important factors in the suitability of a metal for bending.

The most significant difference between bending and stretching is the role of microscopic impurities or inclusions that are not metallic. They are introduced during the solidification of the metal as it is made in bulk form at the mill. During hot-rolling they become elongated into "stringers." In bending the stringers cause premature failure if they are oriented perpendicularly to the direction of the bend. If the material is



ELONGATION UNDER LOAD is tested by pulling a piece of sheet metal to failure in tension. The point where the colored curve turns to the right is the yield point; thereafter the shape of the metal changes permanently. Beyond that point the metal continues to harden as it elongates, so that it is able to carry an increasing load. This intrinsic hardening, termed strain hardening, counteracts the decrease in the metal's load-bearing capacity due to thinning. At maximum load (*peak of curve*) the two forces balance and a process of localization of strain begins, leading eventually to the failure of the metal. The appearance of the metal at various stages is depicted above the curve. At maximum load a diffuse neck appears; near failure one sees a localized neck, where at failure the metal breaks.

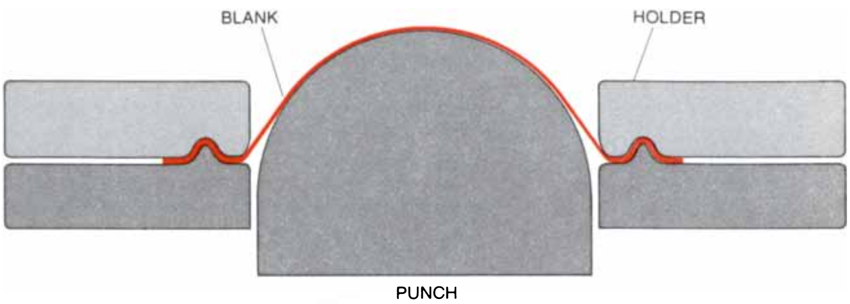
bent with the stringers oriented along the direction of the bend, its normal ductility is maintained [*see bottom illustration at right*].

This difference between longitudinal and transverse bendability is not always revealed by tensile tests. In the recently developed high-strength low-alloy steels the shape of inclusions has been controlled by adding during casting minute amounts of rare-earth elements such as cerium. Cerium combines with the inclusions of manganese sulfide that are usually present and makes them strong at the temperatures at which the steel is rolled. Hence the inclusions are not deformed with the rolling of the ingot. They remain spherical and therefore do not impart the undesirable transverse-bending properties.

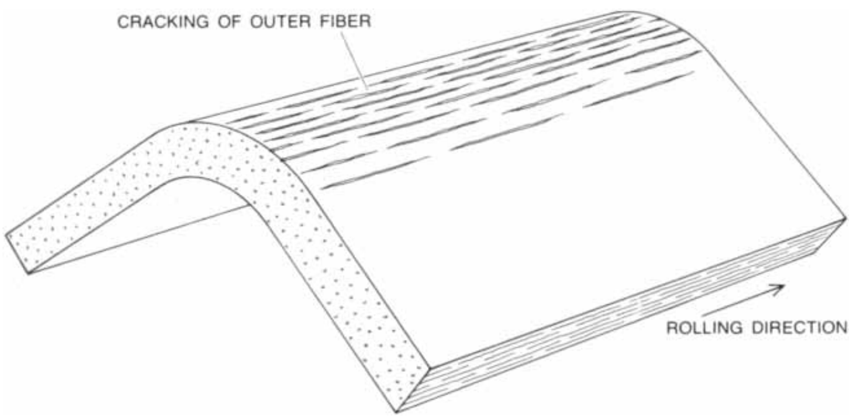
For many years low-carbon steels have satisfied almost all the requirements for the forming of sheet metal. They can withstand well the deformation inherent in forming. Steels can be produced with favorable plastic anisotropy, respectable strain hardening and strain-rate hardening and a high forming-limit curve. Enormous quantities are produced at low cost. Moreover, low-carbon steel possesses excellent stiffness and good strength, so that it meets many structural requirements, and it has a good surface finish.

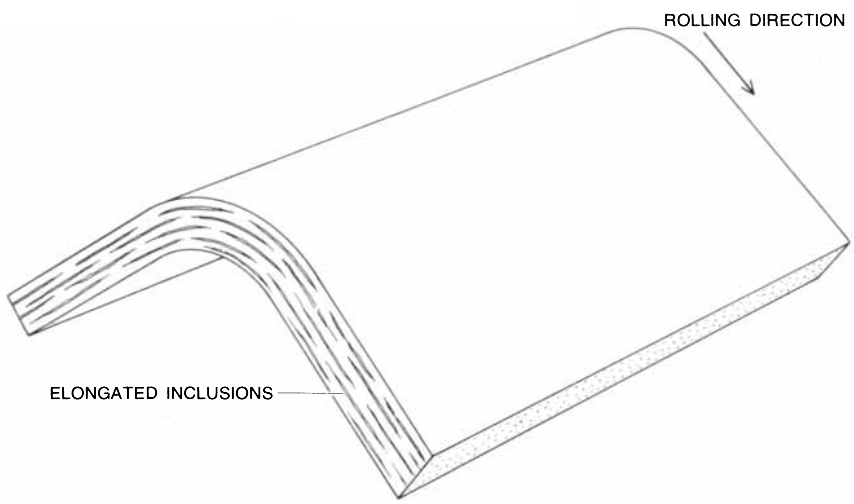
Recent trends in the automobile industry, however, have emphasized reducing the weight of the vehicle to keep down the consumption of fuel while at the same time employing material that has a high strength and can absorb energy well in collisions. As a result materials such as aluminum alloys and high-strength steels, which have higher ratios of strength to weight than low-carbon steels, are being introduced in automobiles. Such materials are much more difficult to form than the conventional low-carbon steels, and production experience is lacking. The selection of metals for stamping has been greatly facilitated by laboratory studies of the simple forming processes we have described. It is now realized that the choice of the proper laboratory test depends on the shape of the stamping and the mode of forming. If the critical mode of stamping can be identified, that is, if it can be ascertained whether the part will be mainly drawn or mainly stretched, then selecting the proper material is easier.

The major problem in studying sheet forming analytically is to predict the patterns of deformation. Since the deformation occurs in various ways and in various places, mathematical calculations based on assumptions of simplified stress states and idealized properties of materials have not yielded acceptable results. More success, at least in predicting the patterns of deformation in simple and symmetrical drawing and

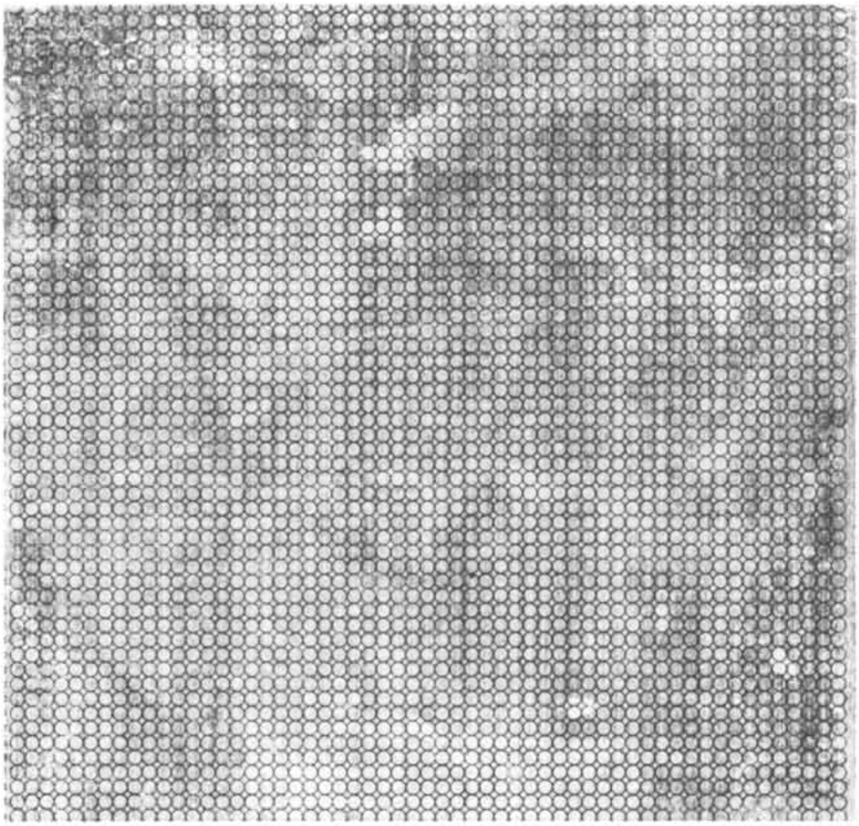


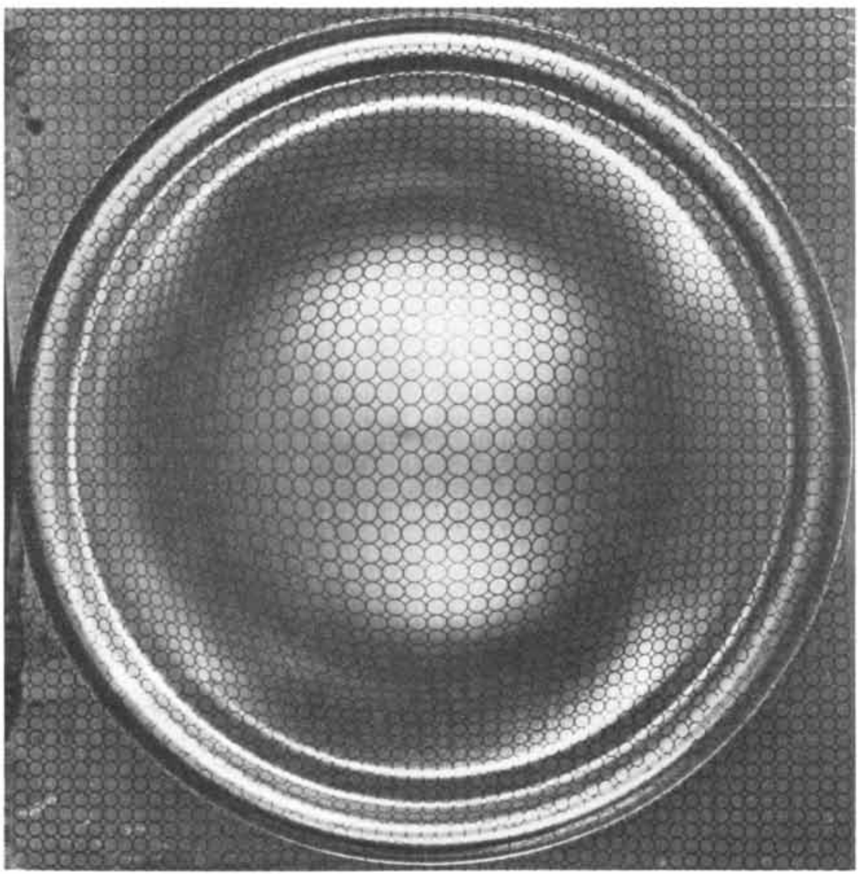
STRETCHING is the second major mode of forming sheet metal by stamping. It is illustrated here by a punch-stretch test that is employed in the laboratory to assess the deformation of a piece of sheet metal during stretching. A metal blank (*color*) is clamped firmly at the edges and then stretched over a hemispherical punch. The groove in the upper die and the bead in the lower one ensure that there is no drawing in of metal, so that the test assesses only stretching.





BENDING OPERATION is often an integral part of sheet-metal forming, particularly in making flanges so that the part can be attached to another part. During bending the fibers of the sheet on the outside of the bend are under tension and the inside ones are under compression. Impurities introduced in the metal as it was made become elongated into "stringers" when the metal is rolled into sheet form. During bending the stringers can cause the sheet to fail by cracking if they are oriented perpendicularly to the direction of bending (*top*). If they are oriented in the direction of the bend (*bottom*), the ductility of the metal remains normal.





CIRCLE-GRID METHOD of testing a stamping is depicted. At the top is a metal blank of steel on which a grid of 2.5-millimeter circles has been imprinted. At the bottom is a domelike form made by stamping a blank in the laboratory apparatus that makes a punch-stretch test. Alteration of circles after stamping reveals the concentrations and amounts of deformation.

stretching, has been achieved with the finite-element method of stress analysis, in which a shape is divided into many small elements and the appropriate equations of stress analysis are solved for each of them. Such an approach is possible only with a modern high-speed computer. Even so, solutions for complex shapes and loading are currently out of reach. Therefore advances in the forming of sheet metal will continue to be partly empirical.

In this context the circle-grid method, which we have mentioned in connection with stretching, has proved to be helpful in the analysis of stampings from the production line. The method was introduced by Keeler as a replacement for the 25.4-millimeter (one inch) squares that were used previously. A quick electrochemical process puts a grid of circles (2.5 or five millimeters in diameter) on blanks of sheet metal. After the blank has been stamped the circles reveal the pattern of deformation. Areas of severe deformation are spotted by inspection. A row of circles in such a critical area can be measured and plotted to indicate how severely the deformation is concentrated. Changes in such variables of the stamping process as lubrication, hold-down pressure, draw beads and the size and shape of the blank can now be monitored to see if they really improve the uniformity of strain. In extremely troublesome cases one can measure the strains at various stages of stamping to determine the strain history. Knowing that history, one can hope to avoid such objectionable concentrations of strain.

Circle-grid analysis also serves, in conjunction with the concept of the forming-limit curve, to assess how much a stamping can be deformed without regularly failing. It is valuable also in the preproduction stage, when final changes in dies and in the selection of material are made. The method helps to determine whether the die, the lubrication and the material will result in a satisfactory stamping. Moreover, monitoring the degree of deformation during production runs will indicate whether a less formable (and probably less expensive) material might do the job satisfactorily.

Occasionally difficulties are encountered after long production runs. Stamping a few standard blanks that were set aside previously will indicate whether the trouble results from wear of the die, faulty lubrication or changes in the material. The art of troubleshooting has also been much refined, because the effectiveness of any change made in the production line can be monitored by stamping gridded blanks. Circle-grid analysis has replaced the craftsman's "feel" for the proper flow of the metal, and the forming-limit concept has provided a diagnostic tool for the analysis of failure.

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THE SHAPE OF THINGS THAT WIN

Urban Trees

Only a few trees are suited to cities and can do well in them. The experience of cities in the U.S. Northeast illustrates how appropriate kinds of trees have been selected and improved

by Thomas S. Elias and Howard S. Irwin

How can trees survive in an urban environment? The human artifacts we call cities first appeared less than 10,000 years ago. Trees, which make up some 20 percent of the quarter-million species of modern flowering plants, are the product of an evolutionary process that began in the Mesozoic era. Thus the ancestors of today's trees are some 20,000 times older than the oldest cities. In view of the fact that trees have been exposed to more than 100 million years of selective pressure to adapt to natural environments, it borders on the biologically miraculous that any tree can occupy an environmental niche as hostile as a city street.

Consider the stresses that bear on the average street tree. Even under the most benign circumstances such a tree is as disadvantaged as a tree in the wild would be if it were rooted at the base of some rocky canyon. Like a tree in a canyon it has only a limited exposure to the sunlight that is essential to the process of photosynthesis. It must adjust to an ambient atmosphere (the source of another essential input, carbon dioxide) that on one day may be stagnant and on the next may expose it to winds of gale force. If the canyon tree happens to have little access to the runoff of rainwater, then the street tree resembles it in a third way: the street tree must make do with a subnormal supply of water, another essential input. All these stresses, however, are present in a natural setting. Let us examine some stresses that are unique to the urban environment.

The street tree's already limited ration of sunlight may be further attenuated by urban smog. Its ambient atmosphere may include such common plant toxins as sulfur dioxide from household and industrial furnaces, ozone from the photochemical breakdown of automobile-exhaust nitrogen oxides and more exotic contaminants such as hydrogen fluoride from industrial processes. The urban atmosphere is also laden with the fine particulate matter ejected from smokestacks; the particles cling to the leaves of the tree and interfere with normal transpiration and respiration.

The street tree's water supply, in addition to being subnormal, is laden in winter with sodium chloride and other toxic salts applied to keep streets and sidewalks free of snow and ice. There is another salt load that continues all year round: the urban dog population leaves its territorial signals at the base of the tree. The concentration of urine that results can raise the salt content of the soil above the tree's level of tolerance. Finally, the small volume of urban soil available to a street tree is often inadequate, lacking humus, and is often so compacted that the air spaces between the soil particles scarcely allow either water or air to reach the tree's root system; it may also contain rubble that inhibits normal root growth, and it may be traversed by toxic metal pipes or by steam conduits that expose the root system to lethal heat.

The fact that urban trees manage to survive is certainly not the result of rapid evolutionary adaptations to the city's hostile environment. Neither the 200 years that have seen the rise of the industrial metropolis nor the 100 centuries of coexistence between trees and cities of any kind is a period long enough to have let selective pressures sort out the genes needed to give rise to a cityproof tree. It is man's intervention, not nature's, that has kept trees in the city. A good demonstration of this fact, on which we shall concentrate here, is the succession of street trees in the northeastern U.S. over the past 200 years.

The deciduous trees native to the rural Northeast include many of the first trees to be incorporated into urban environments as clusters of American towns began to coalesce into cities. Among them were hillside species such as the red oak (*Quercus borealis*), the white oak (*Q. alba*), the black locust (*Robinia pseudoacacia*) and the American basswood (*Tilia americana*). There were other valley species, among them the white ash (*Fraxinus americana*), the American elm (*Ulmus americana*), the sugar maple (*Acer saccharum*) and its relatives the silver maple (*A. saccharinum*), the red maple (*A. rubrum*) and the box elder (*A. negundo*). The rural and even suburban durability of these 10 species is indicated by the fact that today they make up nearly 80 percent of the 700-odd deciduous street trees growing in the Dutchess County village of Millbrook, N.Y. Indeed, one of them, the sugar maple, outnumbers the other nine species combined.

In Millbrook the number of American elms has been greatly reduced by the ravages of Dutch elm disease; fewer than 1 percent of the street trees in the village today are elms. This is true not only in the northeastern U.S. but also wherever the elm once flourished. When one of us (Elias) attended a conference at the Urbana campus of the University of Illinois some 18 years ago, both the streets of the town and the campus quadrangle were adorned with these great trees. A few years later virtually every elm had died and had been cut down; the open spaces left by the removal of the trees transformed an inviting human environment into a somewhat forbidding one. The same sorry transformation must have resulted from the great chestnut blight of the early decades of this century, which erased from the American landscape a native shade tree (*Castanea dentata*) that is now remembered almost solely because of Longfellow's line: "Under the spreading chestnut tree. . . ."

Just as diseases have removed the chestnuts and most of the elms from the list of native American trees, so a number of other native trees that do well

AERIAL VIEW OF BOSTON on the opposite page suggests the extent and number of trees found in a typical urban setting. The photograph, made in the infrared from an altitude of about 50,000 feet by an airplane of the National Aeronautics and Space Administration, displays in red what is green on the ground. Much of the red area is trees, which appear both in parks and along city's streets.

enough in such rural settings as Millbrook have been removed from the fully urban environment by undesirable characteristics. The silver maple and the box elder are characterized by soft and brittle wood that splits easily under winter loads of ice or wet snow. When a limb of such a tree breaks off in the country, it is a matter of no great consequence; when the limb breaks off in the city, however, it may create an obstruction or even be a hazard to people walking under the tree. The red oak and the white oak, which put down a deep tap root, seldom survive the process of transplantation, and this, of course, is almost the only means of supplying a city with trees today. The sugar maple, a tree with a noble crown that is not out of place above a village sidewalk, overhangs too much to fit into urban settings that are often only three to six feet wide. The same handicap makes both the black locust and the American basswood poor city-street trees. It is hardly surprising that over the years most of the native American trees of the Northeast have given way to three tree species that are not native and one that is only half native.

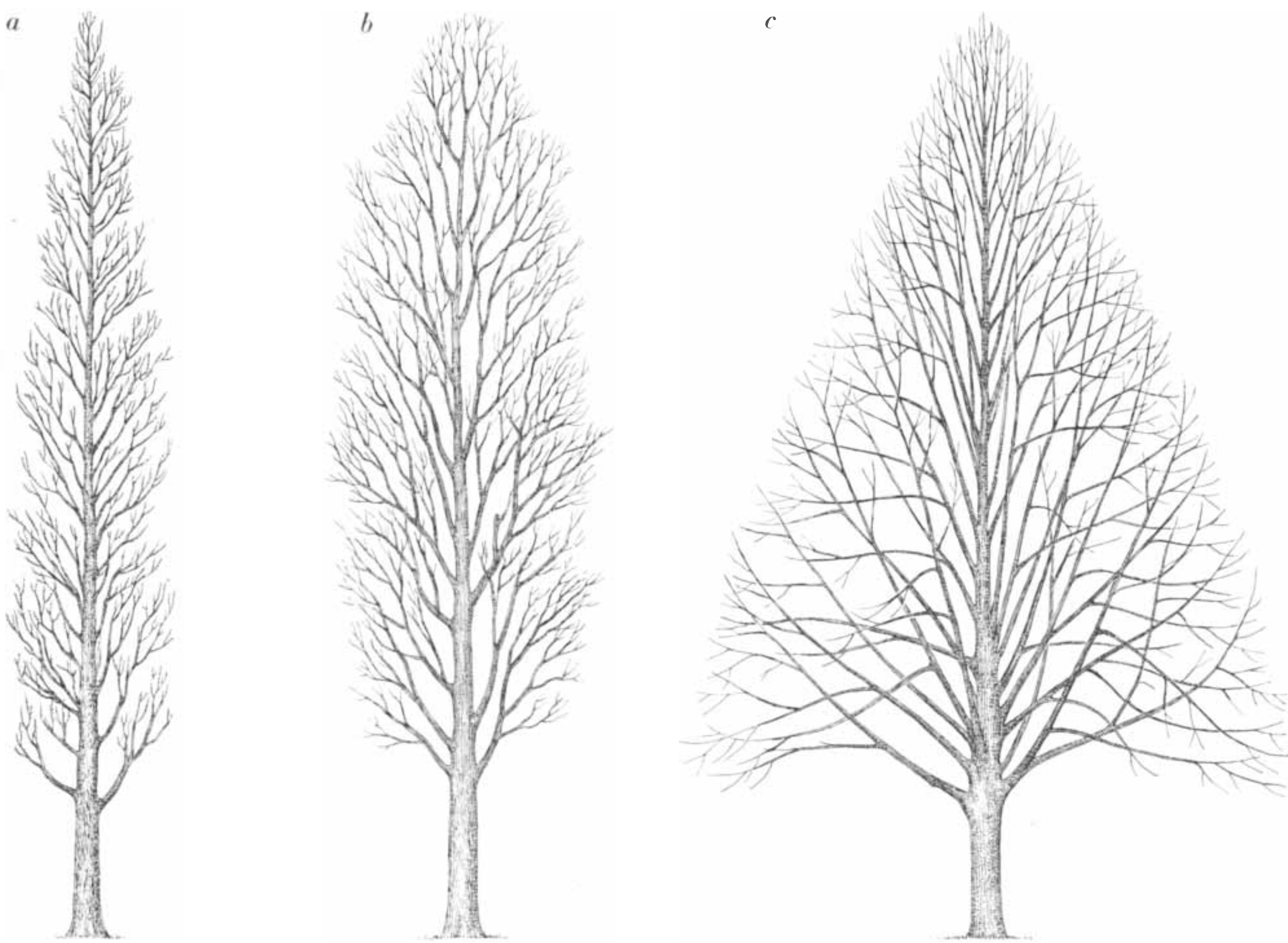
Perhaps the most familiar of the four is the Norway maple (*Acer platanoides*). The species is fast-growing and tolerant of high winds, polluted air and even salt (up to a point). It has been a popular street tree for several decades. As an example, nearly 60 percent of the trees in the city of Poughkeepsie, N.Y., are Norway maples. Nevertheless, the species has its drawbacks. Its height at maturity, 50 to 60 feet, precludes planting it where its crown may interfere with overhead utility wires. (Power and telephone lines are still part of the street scene in a surprisingly large number of American cities.) Moreover, its shallow root system tends to heave up sidewalks. In Poughkeepsie, Norway maples proved to be the culprit in more than 75 percent of 1,217 recorded instances of sidewalk heaving. About one in every five Norway maples had a root system that had dislodged paving stones.

The half-native tree is the London plane tree (*Platanus* X *acerifolia*). It is a natural hybrid between the sycamore, or American plane tree (*P. occidentalis*), and the Oriental plane tree (*P. orientalis*), and it has long been a favored street tree. Today in New York City the London plane is encountered more frequently than any other species.

The second alien tree is demonstrably the most urbane of all, since it is rarely cultivated as a street tree in America but has made its own way as an escaped, self-propagating inhabitant of backyards, alleys and vacant lots. This is the ailanthus, or tree of heaven (*Ailanthus altissima*). Asiatic in origin, the species has been popular in England as a park and garden tree since the middle of the 18th century. In China the ailanthus is grown so that its leaves can be fed to one species of silkworm. In the course of an attempt to introduce silkworm culture to America this species of silkworm was brought from Asia, and the ailanthus was imported at the same time to feed it. The attempt to raise the silkworms was a failure but the tree is still with us.

The third alien tree is the ginkgo, or maidenhair tree (*Ginkgo biloba*), which was unknown outside Asia until the 18th century. Europeans first encountered it as a garden plant in China and Japan, but it remained a rarity both on the Continent and in England until the 19th century. Only male ginkgos are used for urban plantings. The female has been banished because its fruit, when it is ripe, has a strong odor resembling that of rancid butter.

Several other species of trees, both imported and native, may be found on the streets of American cities today. The



BASIC SHAPES for trees on urban streets where air space is limited are fastigiate (*a*), columnar (*b*) and conical (*c*). The three shapes are represented here respectively by the upright ginkgo, the columnar Norway maple and the little-leaf linden, all shown without leaves.

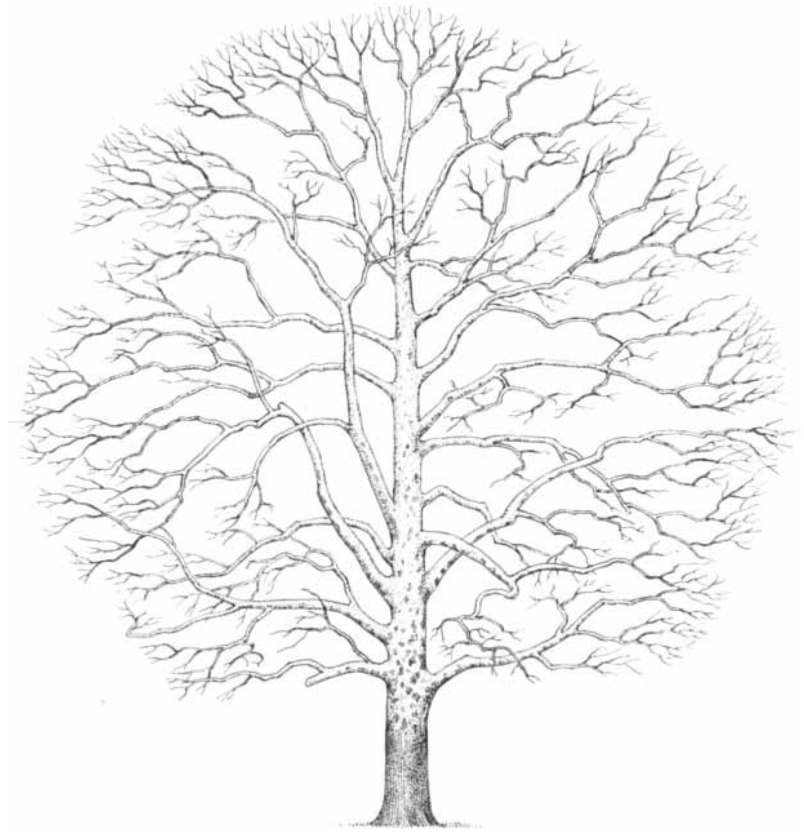
diversity of species reflects not only regional variations in climate but also changes in the approach to urban landscaping during the past half century or so. Some examples of changes in approach are evident in the same survey of Poughkeepsie street trees that produced the pavement-heaving data. The survey, conducted in 1974, made it possible to analyze the approximate dates when various tree species had been planted in that city. Among the native American species a total of 177 red maples were counted; they made up some 2 percent of the city plantings. Only three dozen or so of the red maples, however, had been planted in recent years. Most of the rest were between 50 and 60 years old (to judge from their trunk diameters, which ranged from 21 to 25 inches).

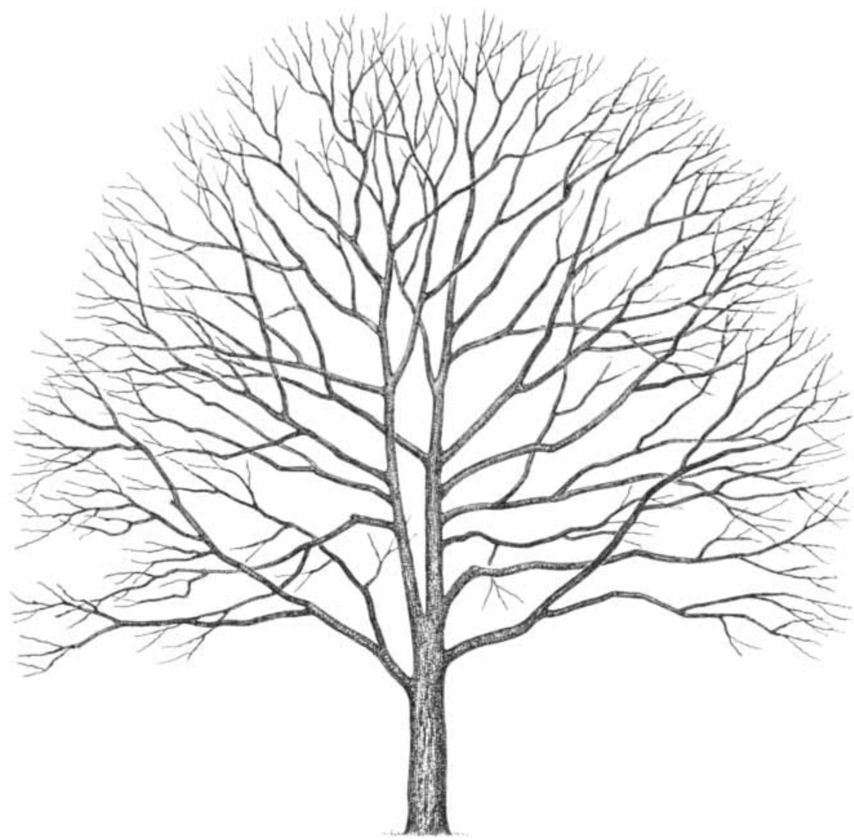
The survey also found that more than 10 percent of the street trees in Poughkeepsie were sugar maples; they numbered almost 900. Only 150 of them, however, had been planted recently. The majority were between 35 and 50 years old (16 to 20 inches in diameter), and nearly 300 of them had been planted more than 50 years ago (21 inches or more in diameter). The same decline in popularity was evident with respect to two other native trees: the American basswood and the silver maple. Of the 300-odd trees of these two species in the city only 12 had been planted recently.

In sharp contrast, Poughkeepsie's principal street tree, the imported Norway maple, was represented by more than 4,500 specimens. Scarcely 10 percent of these trees were old ones. Some 2,700 had been planted between 25 and 50 years ago, mainly to replace the American elms that were dying out in the older sections of the city between 1945 and 1955. Another 1,300, now between one inch and 10 inches in diameter, had been planted even more recently in the process of landscaping new urban-development areas. Other newly popular trees in Poughkeepsie included nearly 1,000 representatives of several species of the crabapple genus (*Malus*), a number of them imports, and more than 100 European lindens (*Tilia cordata*). These newcomers are all under 10 inches in diameter. The crabapples were unknown in the city until 15 years ago.

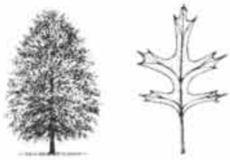
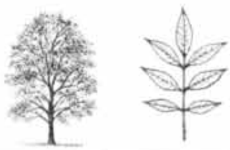
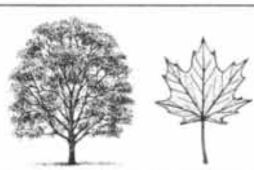
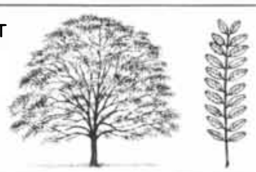
The survey showed that only one native street tree had increased in popularity over the past 50 years, namely the honey locust (*Gleditsia triacanthos*). There is one large honey locust in Poughkeepsie and one of medium size. In the past 10 years, however, 120 of the trees have been planted. As we shall see, this native owes its increasing favor as a street tree to special circumstances.

How has man's intervention led to the development of trees suited to the urban environment? Orchardists and nurserymen know as well as botanists that the





BROAD SHAPES are also suitable in urban environments such as parks and streets where air space is not a seriously limiting factor. Typical shapes are the global tree (*top*), represented here by the London plane, and the spreading branched tree (*bottom*), here the thornless honey locust. Among basic broad shapes one also finds broad oval trees and vase-shaped trees.

SPECIES	GROWTH RATE	GROWING CONDITIONS	HARDINESS ZONES
PIN OAK *QUERCUS PALUSTRIS* 20 TO 25 METERS 	MODERATE TO FAST	FULL SUN. RICH, LOAMY, WELL-DRAINED, SLIGHTLY ACIDIC SOIL.	4–8
WILLOW OAK *QUERCUS PHELLOS* TO 18 METERS 	MODERATE TO FAST	FULL SUN. RICH, WELL-DRAINED, ACID SOIL	5–8
UPRIGHT GINKGO *GINKGO BILOBA* "FASTIGIATA" TO 18 METERS 	SLOW	HIGHLY TOLERANT OF URBAN CONDITIONS.	4–8, INCLUDING CALIFORNIA
GREEN ASH, *FRAXINUS PENNSYLVANICA* "MARSHALL'S SEEDLESS" TO 20 METERS 	FAST	FULL SUN. LOAMY, WELL-DRAINED, NEARLY NEUTRAL SOIL.	3–8, INCLUDING CALIFORNIA AND PACIFIC NORTHWEST
MODESTO ASH *FRAXINUS VELUTINA* VAR. *GLABRA* TO 20 METERS 	FAST	TOLERANT OF DRY, ALKALINE SOIL.	5–8, PARTICULARLY CALIFORNIA AND SOUTHWESTERN DESERT AREAS
NORWAY MAPLE *ACER PLATANOIDES* 12 to 30 METERS 	MODERATE TO FAST	FULL SUN. TOLERANT OF POOR SOIL.	3–10, EXCEPT SOUTHERN CALIFORNIA AND SOUTHWESTERN DESERT AREAS
JAPANESE PAGODA *SOPHORA JAPONICA* "REGENT" TO 20 METERS 	SLOW TO MODERATE	TOLERANT OF POOR SOIL. DOES BEST IN NEARLY NEUTRAL, WELL-DRAINED SOIL.	4–7
THORNLESS HONEY LOCUST *GLEDITSIA TRIACANTHOS* VAR. *INERMIS* "SHADEMASTER" TO 25 METERS 	FAST	FULL SUN OR PARTIAL SHADE. TOLERATES DROUGHT AND RANGE OF SOIL CONDITIONS.	4–10
SERVICEBERRY *AMELANCHIER CANADENSIS* OR *A. LAEVIS* 7 TO 12 METERS 	MODERATELY FAST	PARTIAL SUN. MOIST SOIL.	4–8
GRECIAN LAUREL *LAURUS NOBILIS* TO 10 METERS 	SLOW	FULL SUN. WELL-DRAINED ACID OR ALKALINE SOIL.	7–8, INCLUDING PACIFIC NORTHWEST, NORTHERN CALIFORNIA AND SOUTHERN STATES

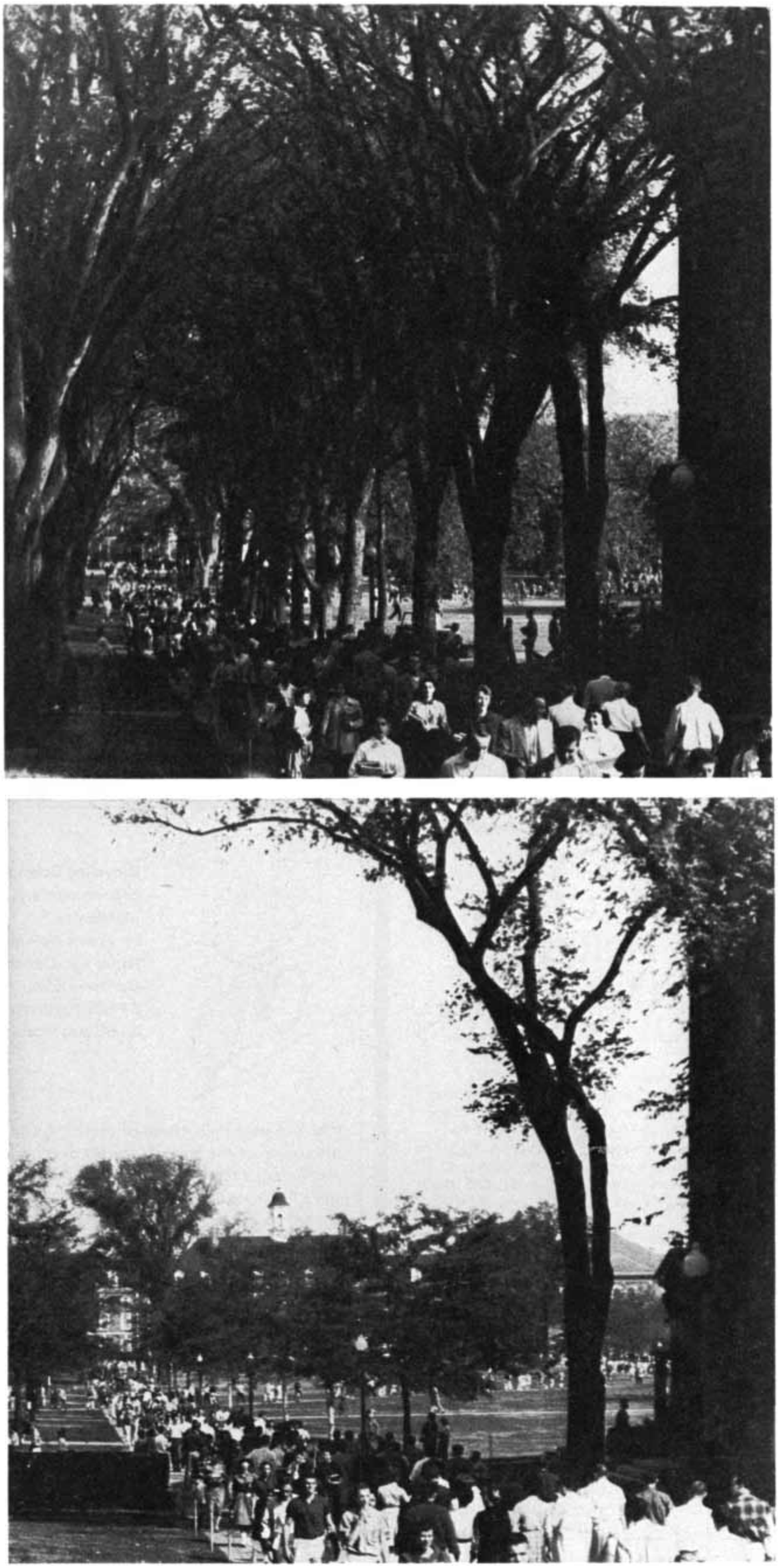
SUITABLE TREES for an urban environment are shown in an arrangement that includes a representation of the shape of the mature tree, the appearance of one of its leaves and a statement of the main properties that make the tree desirable in a city. The list is selective, being oriented to the conditions in large cities. Hardiness zones of U.S. and part of Canada are shown on map on pages 116 and 117.

selective breeding of trees to obtain and then stabilize desirable characteristics is time-consuming. To be sure, the natural range of genetic variability within a single species of tree is often huge. Yet if one is to take advantage of this variability, it is first necessary to identify the particular variants within the species that have the desired characteristics. Moreover, even after the selected races have been located and bred one cannot be sure that the progeny raised from seed will exhibit the parents' favorable characteristics. The natural process is a lengthy one of try, discard and try again, and one can conservatively predict a 25-year interval between the production of the first cross and the maturation of a testable hybrid. Fortunately for centuries a simple way to shortcut the natural process has been known both in principle and in practice. It takes advantage of the plant kingdom's capacity for asexual reproduction. The botanist calls it vegetative reproduction.

Whereas the oldest broad-base selection and breeding program using a wide range of genera to produce street trees is only 19 years old, certain street-tree species have been propagated by cloning techniques for generations. An example is the ginkgo. Since only male ginkgos are planted in cities it would be a waste of time and effort to raise ginkgo saplings from seed and then discard the unwanted female trees. Instead cuttings from a wide variety of male ginkgo clones are induced to form their own root systems; the rooted clonal offshoots, all male, are then transplanted. The same procedure is followed with the green ash (***Fraxinus pennsylvanica***), and for a similar reason. The fruit of the female green ash is not noxious, but it would add unwanted litter to the city streets. The tree's deep root system, however, makes the species tolerant of urban drought and salt load; as a result cuttings from male trees are rooted for transplantation.

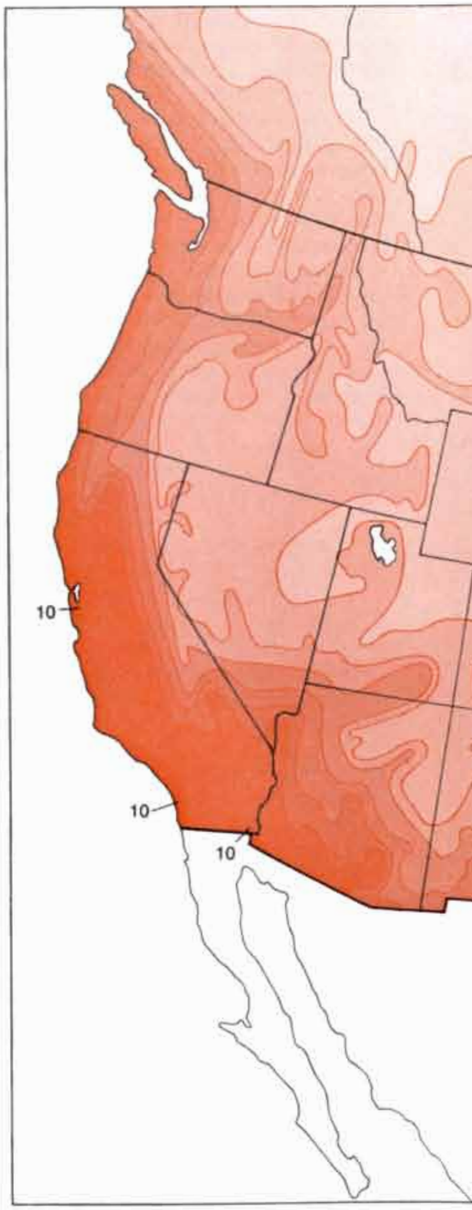
To root a cutting is not the only technique of clonal propagation for obtaining genetically desirable street trees. For example, the rootstock of one race may be particularly resistant to subsurface urban stresses, but the race may also be wide-crowned or may reach undesirable heights at maturity. If another race of the same species grows up short and narrow, both races may be raised in the nursery. The nurseryman will then cut the hardy-rooted race close to the ground, discard the stems and graft in their place the amputated stems of the race with the desired pattern of growth. Because the surgery is done low on the tree, nurserymen refer to these asexual by-products of two separate races as low grafts. Most clonally propagated street trees are produced by such a grafting procedure.

An example is the honey locust. The



DECLINE OF ELM, once one of the commonest city trees, has resulted from the spread of the Dutch elm disease. The effect appears in these photographs made from the same place on the campus of the University of Illinois at Urbana in about 1945 (*top*) and some 15 years later. Elms that were removed along the walk were replaced by the thornless variety of honey locust.

native *Gleditsia* can grow more than 100 feet high. Its trunk tends to be crooked, and it is armed with long, branched thorns that are a menace to the unwary passerby. It also bears fruit in the form of large twisted seedpods. In short, above the ground the honey locust is poorly suited to being a street tree. Nevertheless, it is tolerant of drought and can survive relatively heavy salt loads. Over the years repeated trial growths of honey-locust seedlings eventually gave rise to a clone that is thornless, bears almost no seedpods and has a straighter trunk. Three separate selections of this thornless clone are now regularly propagated as cuttings and then grafted to the drought- and salt-resistant rootstocks of the native honey locust; these are the



HARDINESS ZONES of the U.S. and part of Canada reflect differences in the average

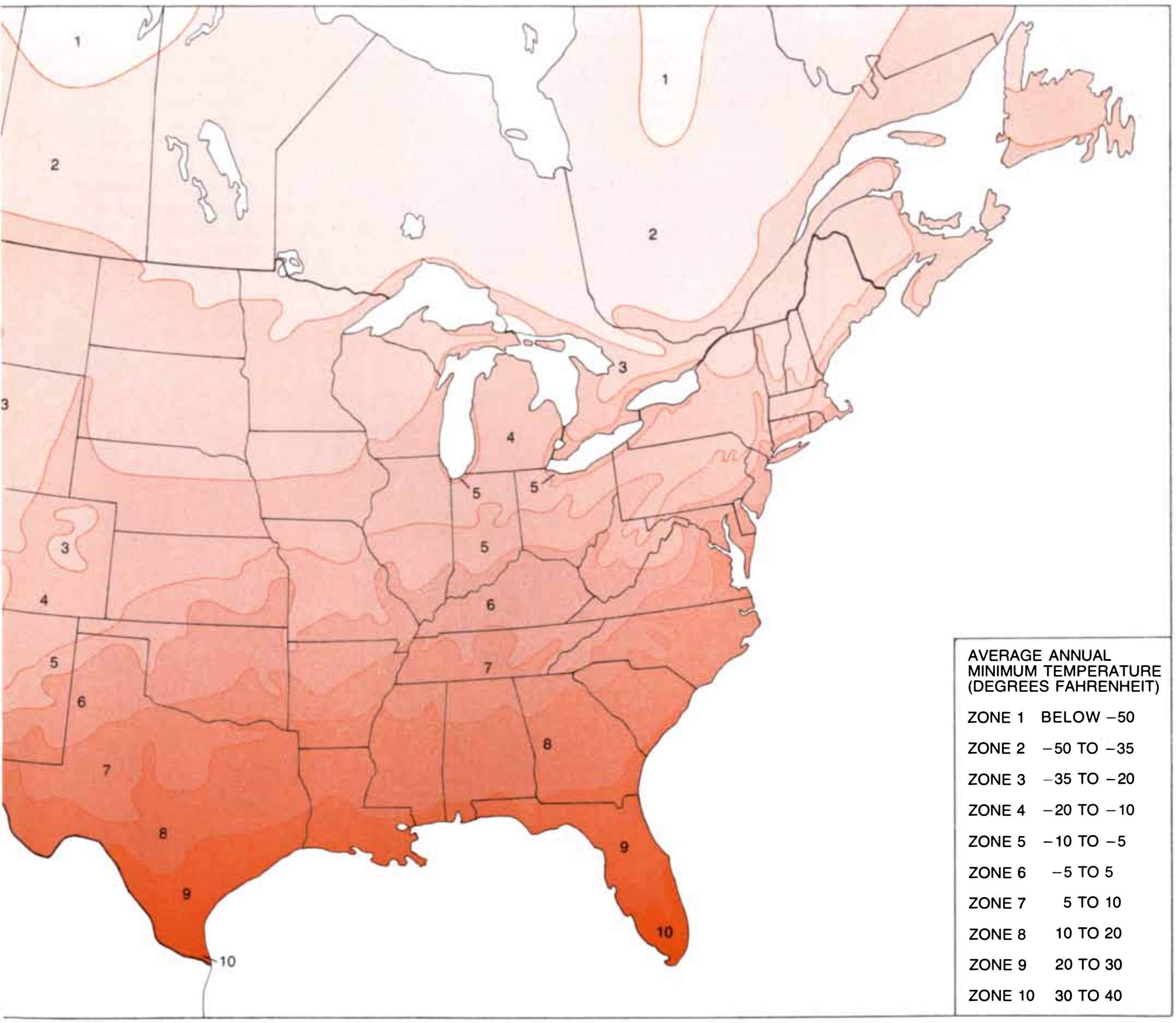
improved trees that account for the increasing favor of the species.

The European little-leaf linden (*Tilia cordata*), an imported street tree of increasing popularity, is another beneficiary of cloning. In nature its races vary considerably in size and shape, with the largest often reaching a height of 80 to 90 feet at maturity. Intensive selection has produced clones that combine moderate height with a good rate of growth and a silhouette that becomes progressively narrower toward the top. Selections from these clones have proved to be particularly well suited to city streets.

The white ash, a native tree, provides an example of a different cloning technique. There are male clones of this species with leaves that become a deep purple in the fall; the lively coloration can relieve the uniformity of many city settings. It is difficult, however, to distinguish between a male and a female white ash when the trees are young. To ensure a supply of the males, nurserymen graft buds taken from known male clones to an ordinary white-ash rootstock.

Male clones of two other trees, both of them alien, seem assured of a place as urban street trees. One, a native of Japan, is the katsura tree (*Cercidiphyllum japonicum*). It grows rapidly, and its small heart-shaped leaves afford ample shade while producing less litter than the larger leaves of other street-tree species. The fall coloration of the katsura tree's leaves is yellow and red, adding to its attractiveness. The other alien clone, from Siberia, is the Amur cork tree (*Phellodendron amurense*). It is a fast grower and is easy to transplant and establish. The major asset of the Amur cork tree as far as city living is concerned, however, is its tolerance of polluted air.

In the immediate future, then, the trees of our urban streets are likely to be those whose capacity for resisting the stresses of the metropolitan environment has been enhanced by man rather than nature and whose availability will depend on vegetative rather than sexual reproduction. Before altogether writing off nature's capacity for responding to adaptive pressure, however, it may be



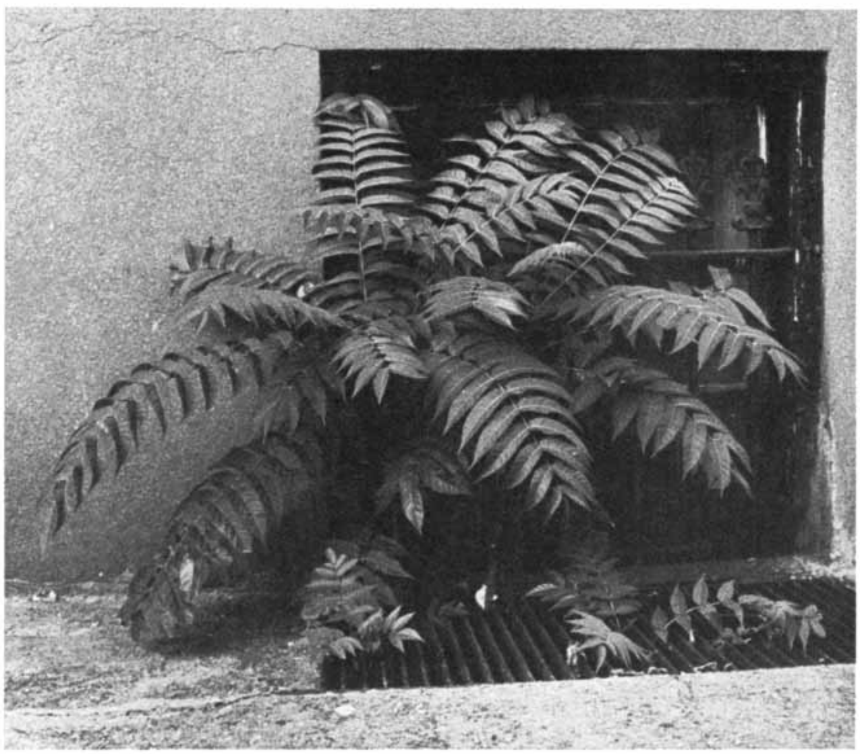
annual minimum temperature and thus differences in the species of trees that can be expected to flourish in each zone. The map is based on a compilation and map prepared at the Arnold Arboretum of Harvard University. Table shows range of minimum temperatures.

salutary to consider a recent observation reported from Montreal. Sugar maples have grown in and around this Canadian city from the time of its first settlement. They are still to be found there, not only in such relatively unpolluted areas as the heights of Mount Royal in the heart of the city but also in such blighted neighborhoods as East Sherbrooke, where oil-refinery effluvia and industrial wastes combine with automobile emissions to make the atmosphere toxic. In the summer of 1974 Gopal K. Sharma of the University of Tennessee collected full-grown leaves from Montreal sugar maples of the same age (judging by their similarity in size) growing in East Sherbrooke, in the somewhat less polluted vicinity of the city's international airport, on Mount Royal and in an unpolluted suburban locality some 40 kilometers outside the city.

Sharma washed the leaves, made impressions of their lower surfaces (where the pores that serve for transpiration are located) and examined the impressions under the microscope. He found that the count of leaf pores on the surfaces of the samples from East Sherbrooke was scarcely 10 percent of that on comparable surface areas of the samples from the unpolluted suburban locality. It was roughly 25 percent of the count on samples from Mount Royal and 40 percent of that on samples from the airport, the next most polluted area. Even more surprising, the leaf surfaces in the East Sherbrooke sample were hairy (the count was nearly 9,000 leaf hairs per square centimeter of leaf surface) and none of the leaves from the other three areas had any leaf hairs at all.

In Sharma's view a change in the number of leaf pores in sugar maples along a gradient that is inversely proportional to the degree of local air pollution is clearly a favorable adaptation, since it minimizes the intake of toxic constituents of the atmosphere, regardless of how it may reduce the efficiency of transpiration and respiration. The absence of any similar gradient with respect to the abundance of leaf hairs is more of a puzzle, but Sharma suggests that when the hairs are present, they provide a covering that protects the leaf against such pollutants as particulate matter.

Does the presence of pollutants in the atmosphere somehow stimulate the development of protective hairs in a species normally lacking them? Is the leaf structure also affected by pollutants in such a way that development of a normal number of leaf pores is inhibited? Or are these observed leaf characteristics the result of selective pressure, working at the level of the gene, that has led coincidentally to the evolution of a race of sugar maples better fitted for survival in an urban environment? Whatever the answers to these questions may be, the Montreal sugar maples offer an intriguing contemporary example of the interaction of a tree and the city.



AILANTHUS TREE that has propagated itself rises through a sidewalk grating in Manhattan. The species was originally imported from Asia so that its leaves could serve as food for silkworms. Silkworm project failed, but the tree has taken hold vigorously in urban settings.

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An Archaic Indian Burial Mound in Labrador

Ancient burial mounds are usually associated with large, stable agricultural societies. Yet the oldest mound known, now found on a subarctic shore, was made by a band of hunters and gatherers

by James A. Tuck and Robert J. McGhee

The ancient practice of raising mounds over the graves of important people is known from examples in both the Old World and the New. Considering the wealth of grave furnishings many of the mounds contain and the number of man-hours needed to put up even a modest mound, prehistorians generally view mound burials as indicating a stable social organization, a good-sized population and an economy based on agriculture and animal husbandry. Thus it comes as a surprise to learn, as we and our colleagues did recently, that the earliest burial mounds known anywhere in the world were built more than 7,000 years ago not by some settled, well-off people but by bands of Archaic Indian hunter-gatherers whose homeland was the less than hospitable Canadian subarctic.

The early burial mounds lie in an area astride the Quebec-Labrador border where that dividing line follows a north-south course that ends at the Strait of Belle Isle. The first two mounds were spotted by the Quebec archaeologist René Levesque near Brador in eastern Quebec. Conspicuous piles of rocks had been erected over graves lined with stone. Levesque's excavation uncovered stone knives and projectile points and lumps of red ocher but no human bones, which is not uncommon when burials are in an acid soil.

A third mound, located on the Labrador side of the border some 30 kilometers east of Brador, was found in July, 1973, when our party from the Memorial University of Newfoundland, assisted by a grant from the Canada Council, went to southern Labrador to conduct an archaeological survey of a short stretch of coastline. An earlier reconnaissance of the coast by Elmer Harp, Jr., of Dartmouth College had turned up evidence of human occupation 6,000 or more years ago. We set up camp a short distance from the small village of L'Anse Amour, on the eastern edge of Forteau Bay. That is the location of what is probably the largest archaeological site in southern Labrador: 50 hectares of sand deposits that are constantly shifted by the winds, alternately revealing and concealing numerous traces of human occupation.

On the first day of our survey we noticed what we thought was a kind of boulder pavement, recently exposed to view by road construction that had stripped away the dwarf firs that form an almost impenetrable ground cover in sheltered areas along the coast. We photographed the exposed rocks and calculated that they stood some 28 meters above sea level, but being short of time and manpower and preoccupied with the collection of surface finds among nearby blowouts in the sand, we made no attempt to clear away the rest of the vegetation.

Our 1973 work was successful enough to encourage us to return to L'Anse Amour in 1974 with a larger field crew. The collection of materials from the shifting sands was still our primary objective, but most of the sites of early human occupation were so small that only a few of us could work on them simultaneously. Some of the crew therefore set about clearing away the firs and sand that still covered much of the boulder pavement.

When the pavement was cleared, it proved to be the top of a low mound consisting of small boulders that had been built high enough above the original ground surface for a few of the larger ones to protrude through a zone of turf that had formed and then itself been buried some thousands of years ago. The mound was roughly eight meters in diameter, and the boulders had probably been obtained from the banks of a nearby stream. Each weighed on the average 10 kilograms and was about 30 centimeters in diameter. By the time we had finished we had cleared away some 300 of them. In the clearing process, which we began by removing the sand that had collected between the boulders, we encountered our first artifact: a thin, elongated and smoothly polished stone.

After we had disposed of the sand we mapped and photographed the boulders, marked the mound into quadrants and began the work of removing the surface stones from one of the quadrants. Immediately below the first layer of boulders we found an identical second layer and below that one, toward the center of the mound, we found a third. Under that layer, 45 centimeters below the surface of the mound, we encountered three slabs of rock standing on edge and butted end to end. As we were clearing the quadrant we also noted stains of red ocher. They gave us hope that the upright slabs might be one side of a cist grave: a grave in the form of a stone coffin.

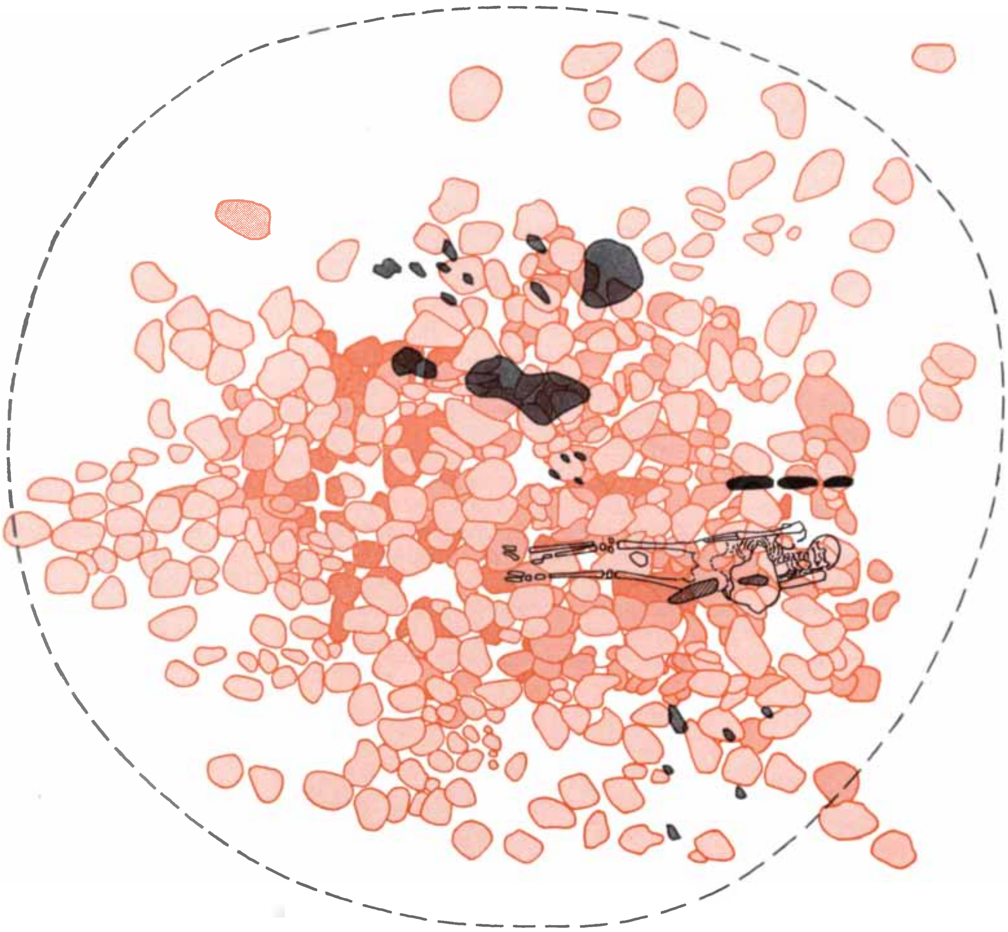
The first quadrant we opened was the southwest one; we now proceeded to open the adjacent quadrant to the northwest. At the same time we extended the overall excavation perimeter two meters to the east so that the cleared area might encompass all of the hoped-for cist grave. It did: a matching pair of upright cist slabs were uncovered as the excavation progressed northward. The northern set of slabs was displaced about 60 centimeters to the east of the southern set. Having got this far, we decided to remove all the boulders in the two remaining quadrants and excavate the entire mound area down to the top edges of the cist-grave slabs. In so doing we could record any traces of human activity that might still be hidden anywhere in the mound area.

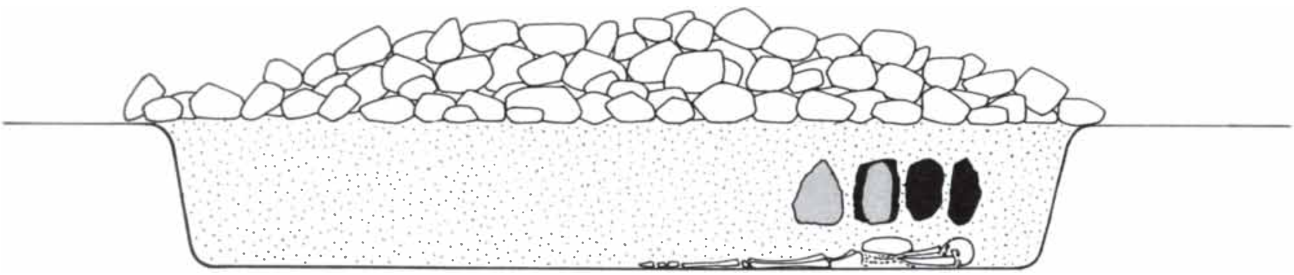
This step in the excavation produced no results, and so we turned to removing the sand lying lower than the top edges of the slabs. As we proceeded we were encouraged by uncovering several more traces of red ocher. At the same time our digging became increasingly difficult because the loose sand walls of the excavation kept slumping. To avoid further caving in we enlarged the area of excavation until it took the shape of a seven-meter square with walls that sloped at an angle too shallow to be subject to slumping.

We progressed from the top of the cist slabs, some 45 centimeters below the surface of the mound, to the base of the slabs, about a meter below the surface, without finding any trace of a burial. Only a few organic stains marked the sand we removed; they may have been traces of decayed wood or bark. We were disappointed, but we went on to map the position of the upright slabs, removed them and continued to dig deeper into the apparently sterile sand. Our efforts were rewarded when, 130 centimeters below the surface of the mound, a vivid patch of red ocher appeared in the sand near the west end of the cist grave.

As our excavation exposed more of the ocher-stained sand we found that it lay above the side of a human skull. A few more hours of painstaking sand removal revealed an almost intact skeleton, located below the cist slabs but within the rectangle formed by them. It was lying in an east-west orientation and in a prone position. The skull was at the west end of the grave, turned so that it faced north.

The skeleton was accompanied by a number of artifacts. Directly in front of the face was a large walrus tusk. Beside the left shoulder were two large knives made of chipped pink quartzite, and between the femurs was an oval stone knife made of chipped dark quartzite.





BURIAL MOUND excavated by the authors and their colleagues at L'Anse Amour in southern Labrador is seen in two views. The plan (*top*) shows successive layers of boulders (*lower layers in darker color*) encountered during excavation and locates the upright slabs of stone and the skeleton below them. The elevation (*bottom*) shows the mound as it probably appeared soon after construction, before the sand filling the burial pit and the 300 boulders in the overlying layers began to settle. The excavators, using long-handled spades, expended 250 man-hours removing the sand from the pit and 50 more removing the rocks. The Archaic Indians, with nothing but improvised spades for digging and refilling the pit, must have invested much more time: perhaps a week if the group included 15 to 20 families.

Near the pelvis were two graphite pebbles that showed signs of rubbing and gouging; both were enveloped in red ocher. (When graphite and ocher are mixed, they form a "metallic red" pigment.) A small bone tool made from the base of a caribou antler and also enveloped in ocher was next to the graphite pebbles; it may have been a pestle for grinding and mixing the pigment.

Under the rib cage of the skeleton was a tapered pendant made of bone or antler. It was decorated with a series of incisions and perforated, as if for stringing, at its narrow end. The perforation had been made by gouging or incising rather than by drilling. Nearby was a whistle made from the long wing bone or leg bone of an unidentifiable bird. It too was decorated with incisions, and in it were two perforations that allowed variations in the pitch of the whistle. The instrument had been broken just at the point where traces of a third perforation were visible. The broken area had been repolished, however, before the whistle was placed in the grave. The instrument still produces a shrill note when it is blown.

On the west side of the skull we found another stain that was brownish rather than reddish. As we cleared away the sand we found a small cache of grave offerings: two small projectile points, one made from pink quartzite and the other from translucent and mottled vein quartz; two larger projectile points, slightly asymmetrical and made from the same materials; three socketed bone points made from the hollowed-out ulna bones of caribou, and a partly decomposed, stemmed bone point made from a long bone of an unidentifiable large mammal.

On top of the skeleton's rib cage rested a large flat rock of the same kind we had found at the sides of the cist grave. On both sides of the skeleton, particularly around the legs and the feet, were traces of organic material that on examination proved to be almost completely decomposed wood. This material may be the remnant of wood spear or harpoon shafts long since decayed beyond recognition; alternatively it may indicate that the grave had a coffinlike lining of wood or bark.

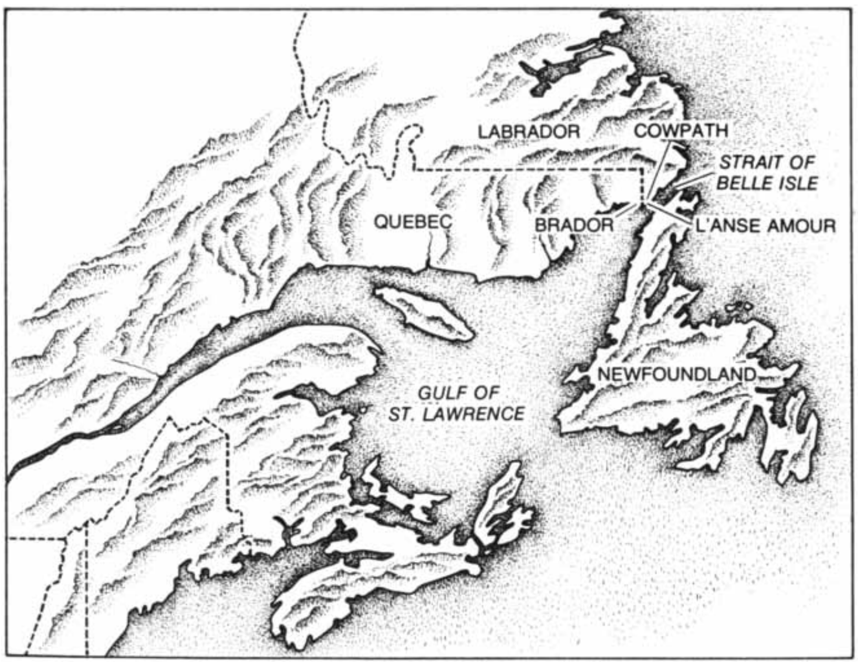
After we had completed the exposure of the skeleton and its associated artifacts the depth of the grave excavation was some 150 centimeters below the top of the mound. On both sides of the skeleton we uncovered concentrations of charcoal: the remains of a pair of open fires. Nearby, to the south, was a stain in the sand that was almost jet black. Digging into the stained area, we found the remains of a large section of caribou antler. It is a good candidate for a tool used by the Archaic Indian hunters to scoop out the sandpit underlying the burial mound.

We sent samples of the charcoal from the two graveside hearths to two different laboratories for carbon-14-dating analysis. The measurement made by the firm of Isotopes, Inc., yielded a date of $7{,}530 \pm 140$ years before the present. The second measurement, made at the Smithsonian Institution, was in good general agreement with the first one: $7{,}255 \pm 85$ years before the present. The age determinations confirmed our suspicion that the mound burials in this area represent remarkably early expressions of ceremony in a population that would ordinarily be considered too lacking in social organization and economic resources to have developed such luxuries.

Stylistically the stone tools Levesque had found in his Brador cairns appear to be as old as or older than those we uncovered at L'Anse Amour, but carbon-14 analysis of organic material from the cairns yielded dates that are much more recent than ours. On the other hand, stone tools unearthed at Cowpath, a site some 20 kilometers north of L'Anse Amour, are almost exactly the same as those found at our grave site, and three carbon-14 dates from Cowpath fall in the same age range as ours. This suggests that the Brador burial mounds and the mound at L'Anse Amour may be related examples of a subpolar Archaic Indian burial tradition of the sixth millennium B.C.

Among the artifacts unearthed with the L'Anse Amour skeleton are two that have a particular technological significance. One is the oldest toggling harpoon head known; the other is an object that appears to combine the function of a harpoon-line holder and a hand reel. The harpoon head, made from caribou antler, is small and slightly damaged, its tip having been broken off before it was placed in the grave. It is conical in form, with a single pronounced spur at the base; judging by its taper it had originally been somewhat more than 6.5 centimeters long. A conical socket drilled into its base allowed the head to fit over the end of a harpoon foreshaft, and a ridge just above the base probably marks the point where the harpoon line was tied on. The term "toggling" refers to the action of the harpoon head after the harpoon has been driven into the flesh of an animal. Unlike a harpoon head that depends on projecting barbs to keep it from pulling free, a toggling head is held in place by turning sideways in the puncture wound. The presence of the harpoon head in the grave, together with the walrus tusk, confirmed what we had already assumed, namely that these prehistoric hunters not only pursued caribou in season but also hunted sea mammals along the coast.

The line holder is made from walrus ivory and is somewhat more than 16 centimeters long. Slightly curved, it tapers gradually toward both ends. At the middle, where the piece is thickest, a carefully drilled hole extends from the concave face to the convex one. The concave surface is decorated with a series of short incisions not unlike those on the pendant and the whistle. In overall form the artifact is similar to the line holders used by Eskimos today, and it



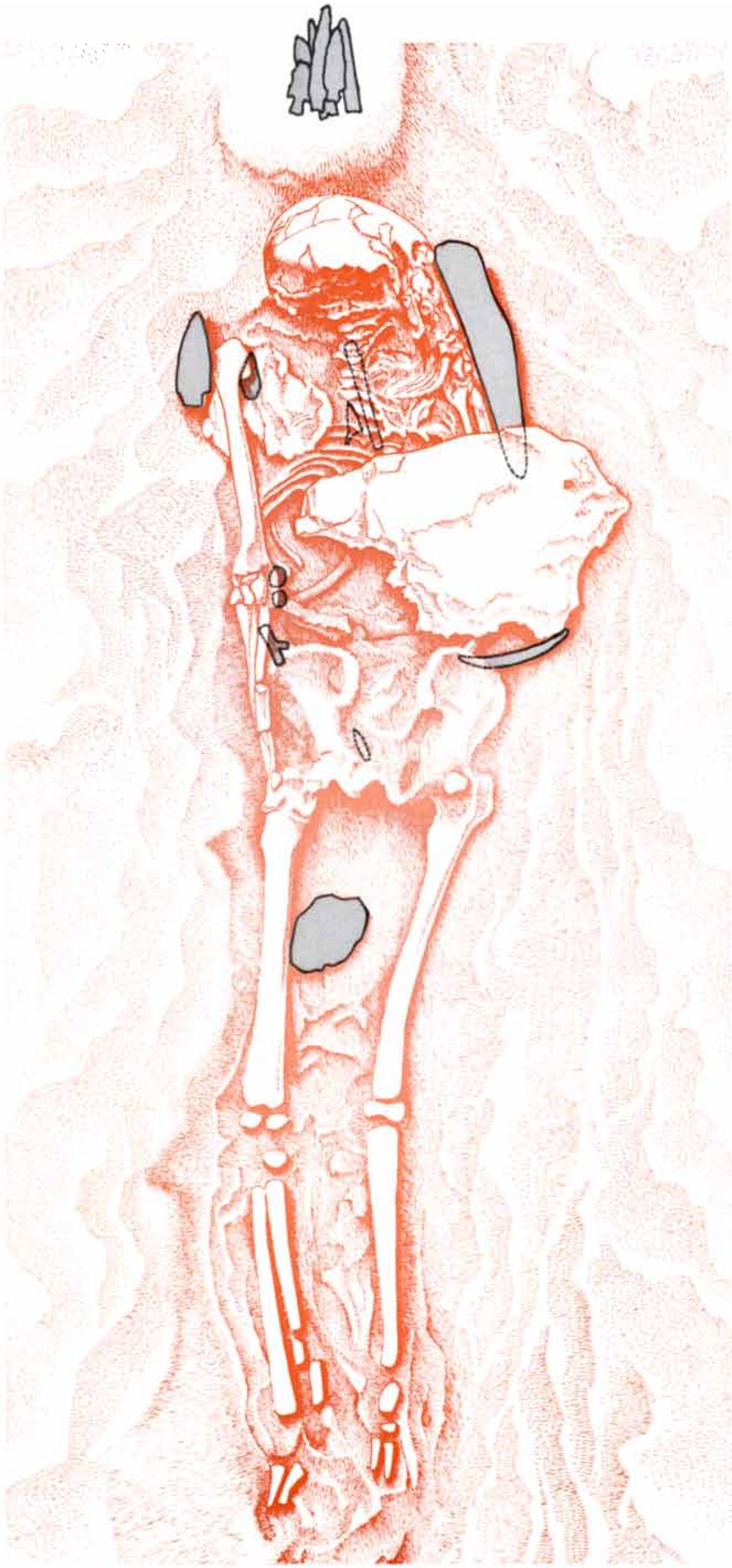
STRAIT OF BELLE ISLE, separating Newfoundland from southern Labrador and eastern Quebec, marks where three Archaic Indian burial mounds have been discovered. Two are near Brador in Quebec; the third, near L'Anse Amour, is in Labrador. A fourth site, at Cowpath in Labrador, does not include a mound but, like L'Anse Amour, is more than 7,000 years old.

seems likely that it served the same purpose 7,000 years ago. Indeed, at the time it was placed in the grave it may have been connected to the toggling harpoon head by a hide harpoon line. Like any wood harpoon shafts that might also have been placed in the grave, the line would have vanished long ago.

The findings we have made in the course of our excavations at L'Anse Amour enable us to reconstruct the sequence of at least some of the things the Archaic Indian hunters did as they raised their elaborate burial mound. For example, the exact outline of the large pit that was scooped out before the body was laid to rest cannot now be traced, but the distribution of the charcoal from the two fires the tomb builders kindled in the pit gives us a good indication of the pit's dimensions and thus of the labor needed to dig it.

It took our team of six, working with long-handled shovels, five days, or a total of some 250 man-hours, to dig down to the level where the charcoal was found. The Archaic Indians, with no better digging tools than caribou antlers and whatever could have been improvised out of wood, must have invested many man-hours more. In this connection, assuming that the Labrador climate was the same then as it is today, the hunting band must have done the digging during the brief summer. From early fall until late spring the ground in the area is frozen to a considerable depth, making excavation of any kind virtually impossible.

After the hunters had dug the pit, they appear to have placed piles of wood on both sides of the area reserved for the body and to have set the piles on fire. By that time the body had presumably been prepared for burial, and it was now placed prone between the two fires. Perhaps some of the objects we found under the skeleton—the harpoon head, the line holder, the graphite pebbles, the pestle and the ocher-and-graphite pigment, the last three perhaps contained in a hide pouch—had been set in place before the body was laid down on an east-west line with the face turned to the north. Other objects, such as the pendant and the



PRONE SKELETON, located 1.5 meters below the top of the mound at L'Anse Amour, is oriented east-west; the skull, at the west end of the grave, is turned so that it faces north. Artifacts buried with the body included a walrus tusk directly in front of the face, two large quartz knives near the left shoulder, an oval quartzite knife between the femurs and an antler pestle and two graphite pebbles near the pelvis. Under the rib cage was a pendant, perforated at its narrow end, and a bone whistle. Nearby were an antler harpoon head, a harpoon-line holder and a cache of large and small projectile points made of quartz and bone. Resting on top of the rib cage was a large flat stone like those around the body.

whistle, may have been attached to the body's clothing or strung around its neck. In any event the stone knives and projectile points, the walrus tusk and the flat rock were placed with the body last of all.

The process of refilling the sandpit then began. If the two fires had not already burned out, they would have been smothered by the sand that now covered the body and the various articles around it. Next the rock slabs were set in place to form the cist, and more sand was scraped up and dumped into and around the cist to raise a mound over the entire burial. Finally, the 300 small boulders were carried up from the stream bank and arranged in layers on top of the mound of sand. Judging from our own efforts in removing and then replacing the layers of boulders, this part of the mound building must have called for another 50 man-hours. For many years thereafter, before the mound began to settle and then was obliterated by drifting sand and encroaching vegetation, the grave site must have been a conspicuous feature of the local landscape, readily visible from anywhere along the shore of Forteau Bay. Even if one generously postulates a hunting band made up of as many as 15 to 20 families in the middle of an easy hunting-and-gathering season that left almost everyone free to take part in the work, the L'Anse Amour burial mound must have taken a full week to build.

Why are there not more burial mounds in this subarctic coastal area than the two at Brador and the one at L'Anse Amour? Even if the custom of funerary rites had endured for no more than a few generations among these Archaic Indians and had been confined to such notables as shamans and hunting-band leaders, the shores of the Strait of Belle Isle should show traces of many more mounds. We have searched without success, however, for both visible features like the mounds at Brador and for others that may now be as obscured as the boulders at L'Anse Amour were. It is notoriously risky to build a hypothesis on such negative evidence as our failure to find more burial mounds. Nevertheless, there are a few items of positive evidence suggesting the possibility that the mound at L'Anse Amour, at least, represents an unusual and rarely performed ritual rather than a routine funerary practice.

The first item of evidence in support of this hypothesis comes from a study of the L'Anse Amour skeleton. Sonja Jerkic of the Memorial University of Newfoundland has identified the skeleton as that of a subadult, sex uncertain, who, judging by the pattern of tooth eruption, was just entering the teenage years. It seems unlikely that one so young would have attained a position in a hunting

LAYER OF BOULDERS that formed the uppermost level of the burial mound is seen here after a dense covering of vegetation was removed and quantities of sand had been cleared from the gaps between the rocks. The average weight of a boulder was 10 kilograms.

EXPOSED BONES, found well below the layers of boulders, are carefully brushed free of sand by two workers from the Memorial University of Newfoundland. The excavators have left in place two quartz tools (*left*) at the level they occupied at the time of burial.

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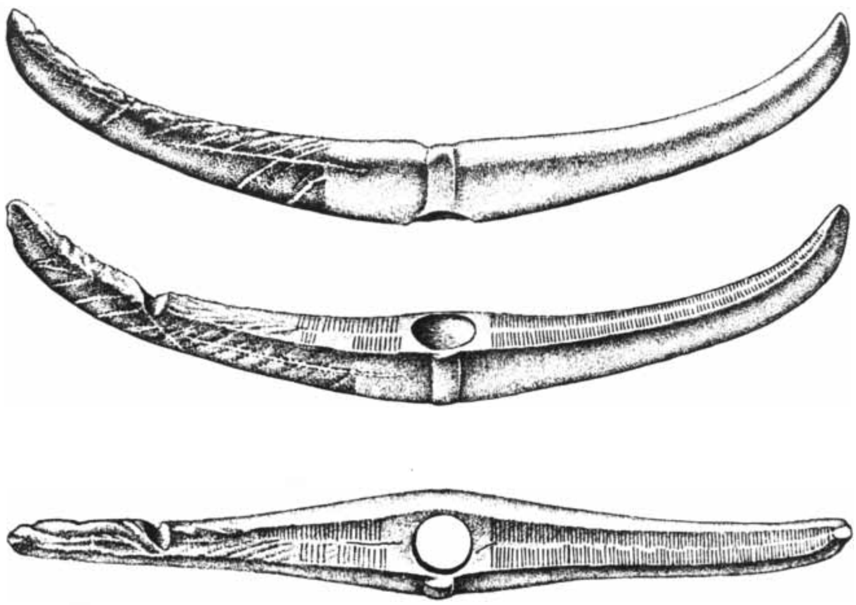
band so influential as to warrant ritual burial. What other motivation might have induced the band to invest so much energy in mound building?

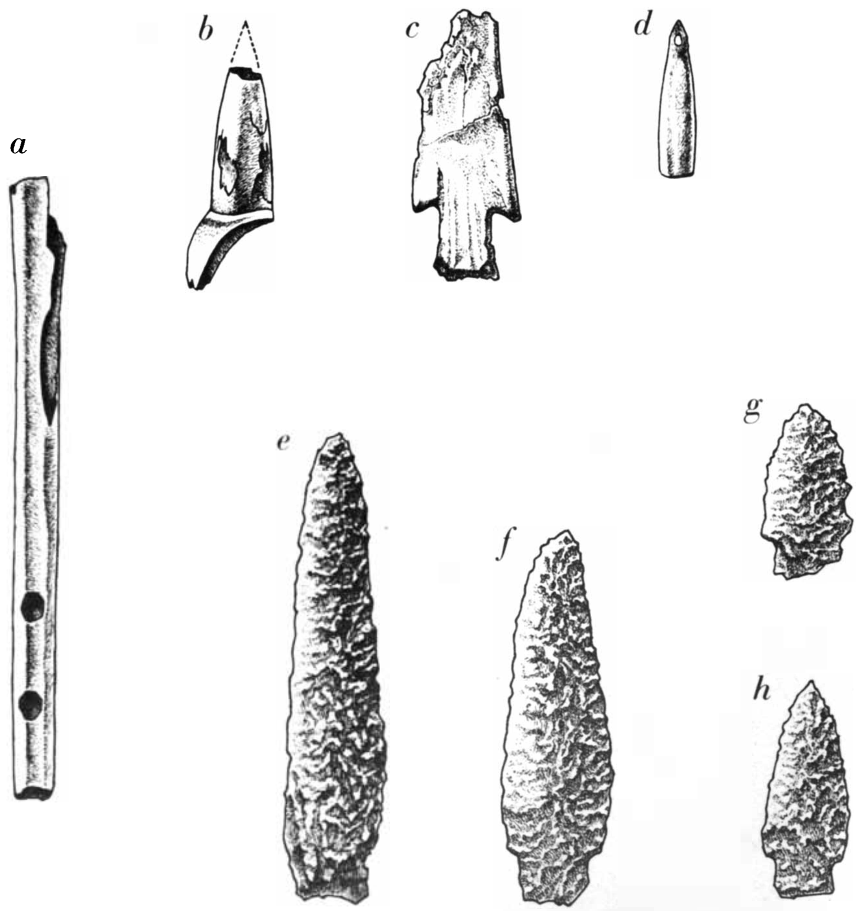
The position of the skeleton and certain other items of evidence is suggestive. When a body is buried in a flexed posture, that is, with its arms folded and its knees drawn up, it is usually placed on its side. By the same token, when a body is buried in an extended position, as the one at L'Anse Amour was, it is usually placed on its back. Burying a body with the back uppermost is unusual. Even more unusual is weighing a body down, so to speak, by placing a slab of rock on top of it. Moreover, one may regard the layers of boulders on top of the L'Anse Amour mound as being additional ballast set in place with the same motivation. The position of the body in the grave, the slab and the boulders all speak the same symbolic message: Stay there!

Why might such a message have been necessary? The skeleton at L'Anse Amour shows no evidence of injury, but this does not mean that the adolescent died a natural death. The cause may have been disease, accidental drowning or a mauling by a bear or a walrus, perhaps the one whose tusk was put in the grave. Any such unnatural death, particularly if the victim was a male who was being instructed in the arts of hunting by adults in the band, might have been considered an event unlucky enough to call for some ritual form of insurance against a similar misfortune's overtaking other members of the community. In other words, perhaps the unusual burial ritual was an effort to lay the victim's ghost. It is even possible, and equally difficult to prove, that these Archaic Indians believed that on certain occasions a young member of the band had to be sacrificed to a deity, and that the adolescent died at the hands of the community. If that is what happened, precautions against the release of an angry spirit would only have been common sense.

Speculations such as these, of course, are little more than exercise for the imagination. The facts from L'Anse Amour are trenchant enough without adornment. A band of Archaic Indians lived here more than 7,000 years ago by dint of a hard annual round of hunting caribou early in the winter and pursuing sea mammals, birds and fish for the rest of the year, eking out their diet with scanty plant foods in season. That these people should have provided anything more than the simplest resting place for one of their number is surprising in itself. The fact that on occasion and for whatever motivation they made a major investment of the community's energies in funerary ritual is something no one suspected until the burial mounds of the Strait of Belle Isle were discovered.



HARPOON-LINE HOLDER, made from walrus ivory, is shown in profile (*top*) and rotated a quarter turn and a half turn (*middle and bottom*). The hole in its center is neatly drilled rather than gouged out. Line holders like this are used by the Eskimos of the Canadian Arctic today.



OTHER BURIED ARTIFACTS included four made of bone or antler: a whistle made out of a long bone of a bird (*a*), a toggling harpoon head made out of caribou antler (*b*) that is the earliest of its kind known, a poorly preserved bone projectile point (*c*) and a pendant of bone or antler (*d*) with a hole, probably for suspension, at its narrow end. The projectile points, made of quartz, are from a cache uncovered near the skull; one of the two larger points (*f*) is shaped eccentrically. All of them testify to their makers' skillful use of the stone as a raw material.

MATHEMATICAL GAMES

In which DM (Dr. Matrix) is revealed as the guru of PM (Pentagonal Meditation)

by Martin Gardner

"Magic makes you question the world. It raises your consciousness. I want to weave together a show so fantastic that people will question their reality." So *The New York Times* for July 9 quoted the magician Doug Henning. The new popularity of magic in the U.S. is surely a spin-off from the occult revolution and represents another response to the public's growing hunger for miracles and mystery. As the cults that feed these hungers continue to expand, many of them imported from the Orient, a colorful new consciousness-raising movement is spreading like a forest fire through the Bengal region of India.

The movement is called PM, an abbreviation for Pentagonal Meditation. Perhaps one reason it is so little known in the Occident is that it had its origin only a year ago in an obscure temple of Shiva on the outskirts of Calcutta, that vast megalopolis that most tourists in India avoid like the plague.

I first heard about PM from my old friend Sam Dalal, a Calcutta magician ("Sam the Sham") who edits (in English) a lively little magic periodical called *Mantra,* to which I subscribe and occasionally contribute. (Anyone interested can write to *Mantra,* Box 6640, Esplanade P.O., Calcutta 700 069.) A newspaper clipping from Sam carried a picture of PM's founder, Guru Marahashish, standing in front of his temple with Zuleika, his assistant. It was hard to make out Marahashish's features because of his bushy white beard and mustache and the long white hair that obscured the sides of his face, but Zuleika's smiling countenance was unobstructed. Although her skin was dark and the caste mark of Shiva—three horizontal lines—decorated her wide forehead, there was no mistaking those lovely Japanese eyes. It was Iva, the Eurasian daughter of Dr. Matrix!

How appropriate, I thought. Remove the first two letters of "Shiva" and you have Iva. I cabled Sam that I would be in Calcutta the following Monday.

It had been 10 years since I last visited Sam, but as the bus creaked and crepitated its way from Dum Dum Airport to the Grand Hotel the old familiar smell of Calcutta assaulted the open windows. It was 4:00 A.M.—hot, foggy and windless. Except for a few new tall buildings the city looked the same. The pavements were littered with the pitiful bodies of the poor, lying under their dirty cotton cloths like corpses under shrouds. Indeed, by daylight many of the bodies would turn out to be corpses. A few cows wandered about looking for garbage. Here and there an early riser was washing himself at a fire hydrant or relieving himself in an alley.

Does any city in the world bring a visitor more starkly face to face with hunger, suffering and death? In Calcutta there is only one way to avoid going mad. You must look on the city as you would a Hollywood set. None of it is real. It is a horror show in living color, thrown on a wide screen for your unwilling fascination.

I found Sam later that morning in his cluttered office on the second floor of a low building in the heart of the city. He too had not changed noticeably: he was still a slim, energetic young man with handsome features, a black mustache and goatee and coal black eyes. Sam is a Zoroastrian Parsee from Bombay. Like all magic buffs we wasted no time on idle conversation but immediately sat down to exchange the latest card tricks.

Sam was eager to meet Dr. Matrix. He knew that the great numerologist had in his youth been an assistant to Tenkai, a renowned Japanese magician, and was said to be skilled in the conjuring art. After lunch we got into Sam's black Fiat and started for the temple, about an hour's drive.

Sam steered his way carefully through the hand-pulled rickshaws. We entered the Maidan, Calcutta's magnificent central park, headed north on Red Road and then swung west to cross the Howrah Bridge. Hundreds of Hindus were bathing below us in the Hooghly River, one of the several mouths of the Ganges. A few thousand Hindus die every year from drinking the holy water, but what does it matter? There is a theory among Calcutta doctors, particularly the homeopaths, that the people who survive gain immunity from Indian diseases.

At the newly renovated temple of Shiva a barefoot Indian boy in spotless white shorts stopped us at the entrance. I was an American journalist, Sam explained, who wanted to write about PM. Could I have an audience with Guru Marahashish?

"We are honored by sahib's visit," said the boy, bowing low.

He strode over to a large bronze *nataraja,* India's traditional statue of a dancing Shiva, to push a button at the center of the god's forehead. Chimes sounded in the temple. A moment later Iva herself, wearing a pentagonally tessellated sari, opened the door.

"Holy cow!" she exclaimed.

We embraced (Iva smelled much better than Calcutta), and after I had introduced her to Sam she led us to her father's office. The temple floor had been recently tiled in a curious periodic pattern that I was told had been designed by Harry Turner, an artist in Cheshire, England [*see illustration on opposite page*]. The pattern seemed to depict a three-dimensional structure, but when you studied it carefully, you saw that the blocks were in an impossible arrangement. The structure could not exist. Huge mirrors covered the walls and ceiling. In every direction I could see hundreds of images of Sam, Iva and myself stretching off toward infinity.

At the entrance to a passageway Iva called our attention to a wood statue of the four-armed Kali, the "bad" form of Shiva's consort and the mother goddess of Calcutta. Legend has it that Kali was once dismembered by Vishnu and one of her fingers fell on the spot that became Kali-cutta: the field of Kali. The goddess's skin was painted black. A scarlet tongue hung from her grinning mouth. At each earlobe a hanged man dangled, and her ebony neck was ringed with a necklace of human skulls.

"Who's the prostrate person she's dancing on?" I asked.

"Her husband," said Iva. "Who else? I'm surprised *Ms.* magazine has never put her on its cover. She's very popular here."

"I sent you a copy of my new Scribner's book, *The Incredible Dr. Matrix.* Did you get it?"

Iva nodded as she opened the office door. "Then I lost it. Once I put it down I just couldn't pick it up again. But you boys must excuse me. I'll see you later."

Dr. Matrix' tall figure rose from behind his desk. His hair and beard were dyed snow white and his skin dark brown, but there was no way short of plastic surgery to alter his enormous hawklike nose. Black eyebrows divided emerald eyes from the painted stripes of Shiva on his forehead.

"Welcome to Calcutta," he said in a

clipped British accent. "Sit down and I'll tell you about PM."

It was in the Himalayas, as a disciple of Swami Fondahondashankarbabasaranwrapi, that Dr. Matrix had learned the five basic principles of PM. The swami, whose smiling oil portrait was on the wall behind Dr. Matrix' desk, called his approach Basic Meditation. Dr. Matrix had changed the name because its abbreviation would give rise to gibes in English-speaking countries.

"The first principle of PM," said DM, "is: What is, is not. We call it nonest. The universe, including you and me, is no more than a monstrous stage illusion conjured up by Brahma while his colleague Shiva dances in the wings. It is all beautifully symbolized in the *nataraja* [*see illustration on next page*]. The universe has just begun one of its endless cycles. The ring of fire is the fireball of the 'big bang.' The drum in Shiva's upper right hand beats out the nonestic rhythms of space-time. The flame in his upper left hand is the energy that upholds and finally devours the world. His lower right hand is raised in a gesture meaning 'Fear not.' His lower left hand points to an uplifted foot that signifies release from the bondage of *maya:* the powerful magic spell that causes the uninitiated to believe the world is real."

Dr. Matrix had picked up a small ivory *nataraja* on his desk. "Who's the dwarf under Shiva's foot?" I asked.

"He's the demon of *avidya,* or ignorance."

"I know about *avidya,*" said Sam. "Only Brahman-Atman is real. The world doesn't exist except in the weak way dreams exist. We are all phantoms in the mind of Brahma, destined like the gods themselves to be absorbed back into the One. Under the spell of *maya* we see the world shattered into many parts. But the parts are only illusions produced by the Great Magician."

Dr. Matrix nodded solemnly while he stroked his beard. Then he clapped one hand and a young Hindu girl entered the office bearing a glass goblet filled with pale red wine. Dr. Matrix placed it in the center of a small circular table that consisted only of a disklike top about a centimeter thick supported by a central rod about a centimeter in diameter and two meters high. He covered the goblet with a tall blue cylinder open at both ends.

"We'll come back to this in a few minutes," Dr. Matrix said. "The second principle of PM is what we call the 'nonest giggle.' It goes like this." Unsmiling, he gave out a high-pitched cackling sound.

"What on earth does that mean?" asked Sam.

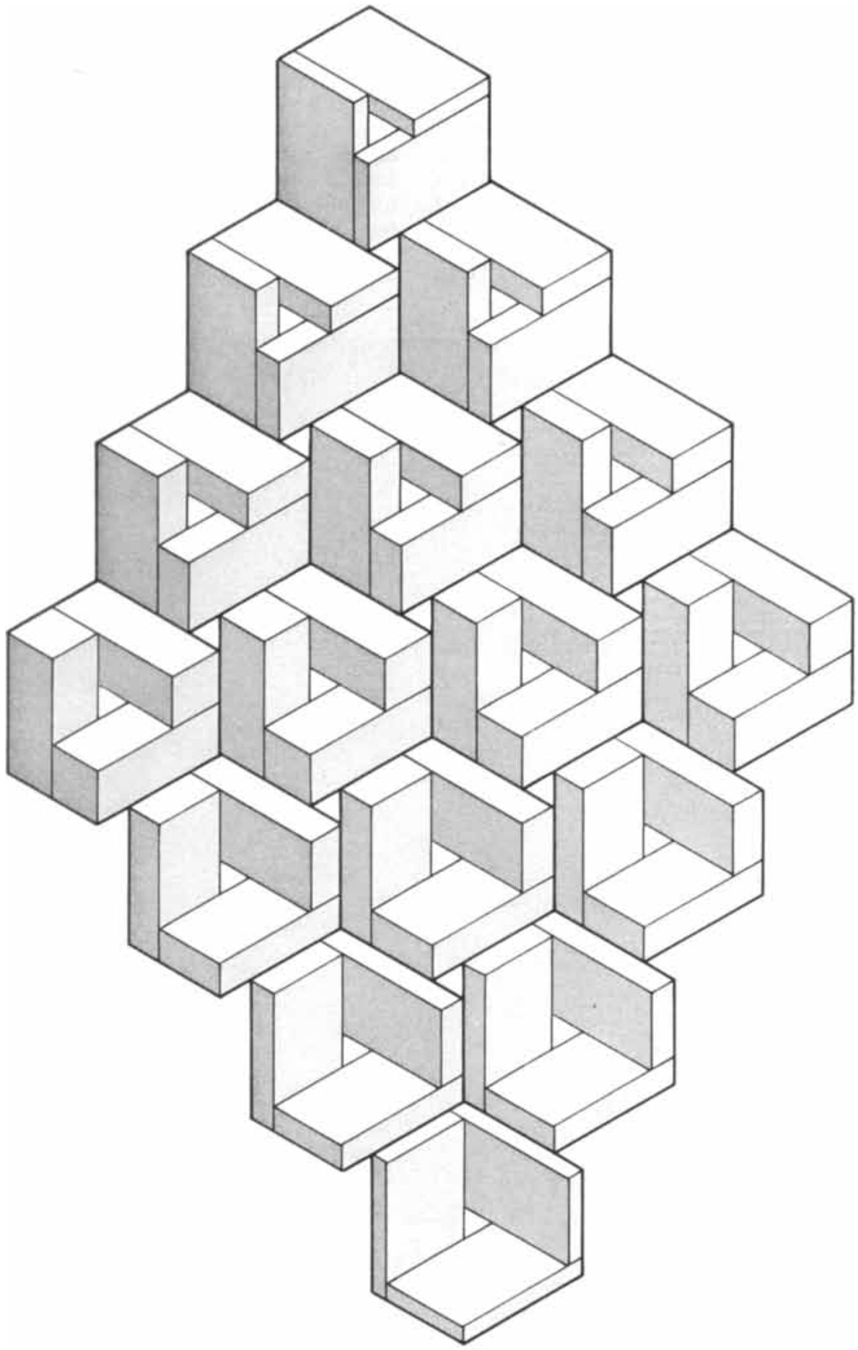
"That," replied Dr. Matrix, "is our technique for reacting to anything that threatens to arouse our emotions. Since nothing exists, there is nothing 'out there' to disturb us. If we pass a crippled, blind or starving beggar, we giggle. If we pass a corpse, we giggle. If we get a headache or any kind of pain, the nonest giggle makes it disappear. Nothing exists, therefore the world is perfect. It is what it is not, so why try to change it? As soon as a student of PM grasps this great truth we say that he or she has 'lost it.' Only by losing all illusions can one find true inner peace and improve one's tennis game."

"Your third principle?"

"It is the sacredness of five—the number of letters in Shiva. Five is the middle digit in the sequence 1 through 9. It is the central digit of the *Lo Shu,* the ancient Chinese magic square of order 3."

"I remember," I said, "that back in 1966, before pi was calculated in France to a million places, you predicted that the millionth digit, counting the first 3 as a digit, would be 5." (See my *New Mathematical Diversions,* page 100.)

"And I was exactly right, was I not? Five is a remarkable number. You must know that in the 17th century Sir Thomas Browne wrote an entire book about the ubiquity of fiveness." (I did not know, but I later checked it out. The



The impossible tiling on the floor of Dr. Matrix' temple book's full title is *The Garden of Cyrus or The Quincuncial Losenge or Network Plantations of the Ancients, Artificially, Naturally, Mystically Considered.*)

"Let's see," I mused. "There are five Platonic solids."

"Yes," said Dr. Matrix, fingering his beard. "And five points determine a conic curve. The fifth degree is the lowest-order equation that cannot be solved in terms of radicals. The number of divisions necessary to find the greatest common divisor of two numbers is never larger than five times the number of digits in the smaller number. All groups of order 5 or less are commutative. There are many other examples."

"Don't forget," said Sam, "that we have five fingers to a hand and five toes to a foot. A starfish usually has five arms. Most flowers have five petals."

"How does five enter into PM training?" I asked.

"It is what our neophytes meditate about. Five times a day, for a five-minute period, they assume the lotus position, close their eyes, breathe through their left nostril and say the word 'five' over and over again to themselves while they picture its numeral in their mind. At the end of each period they chant a secret mantra that we give them as soon as they have brought their teacher three ceremonial gifts."

"What kind of gifts?"

"One is a pocket mirror. Its mirror-image world signifies the illusory character of the world it reflects. Another is a banana. It symbolizes the *shivalinga,* the phallic symbol of Shiva that is worshiped throughout India. Sexual delight, you know, is one of Brahma's greatest illusions. The third gift is the equivalent of an American $50 bill. It is the first of five payments of $50 each. Teachers must donate a fifth of each payment to our temple."

"Only a fifth?" Sam asked.

"Yes. Zuleika giggles all the way to the bank. Our fourth principle is the doctrine of eternal recurrence. We teach that everyone has a thetan body (Christians call it a soul) that goes through five incarnations, each in a different cycle of the cosmos. After each universe is danced into nonest by Shiva it expands for 50 billion years. Then it contracts for 50 billion years and finally enters a black hole."

"The Black Hole of Calcutta?"

Shiva, Lord of the Dance, as sculptured in bronze in India about A.D. 1000

Dr. Matrix ignored my remark, but Sam winced. "After five cycles the universes repeat themselves. Your sixth incarnation puts your thetan back in the first universe, inside the same physical body you had before. We symbolize this with a curious numerical sequence I learned from my juggler friend Ron Graham when I visited him last year at Bell Laboratories in Murray Hill, New Jersey. Do you have a pocket calculator with you?"

"I'm never without one, or a deck of cards," I said, taking an inexpensive eight-digit calculator out of my shirt pocket.

Dr. Matrix handed me a pad and asked me to jot down any two real positive numbers. I wrote pi and 76. He asked me to add 1 to the second number and then divide the sum by the first number to get the third number of the sequence. I entered 76, added 1 and divided 77 by 3.1415926. The result: 24.509861. To get the fourth number I repeated the recursive procedure: add 1, then divide by the previous number. This yielded .335656. The fifth number was .0544946.

"Now," said Dr. Matrix, "for the zonk. You probably would guess that if you continue applying the algorithm, you will get more and more horrible numbers. But try it once more and see."

I was zonked all right. The next number was pi! The readout was 3.1415931, but that was because tiny errors had accumulated in the machine. Dr. Matrix assured me that when all calculations are accurately made, the sequence loops with a period of five. It is easy to prove, but I leave the proof as a problem to be answered here next month.

Dr. Matrix showed us several other calculator curiosities involving five, but I have space for only one more. Enter 555 and divide five times by 5. The results are 111, 22.2, 4.44, .888, and finally the year of American independence, .1776. Try starting with a row of as many 5's as your readout takes.

"And the fifth principle?" asked Sam, who had been taking notes.

"It is our Supreme Principle. We reveal it only after a student has made his fifth payment."

"What's happening there?" I asked, pointing to the blue cylinder.

"Something nonestic," answered Dr. Matrix. "Kindly lift the tube."

When I did, I could not believe my eyes. The goblet and its contents had vanished! I examined the cylinder. There was nothing suspicious. Sam was smiling enigmatically. Later he told me that he himself had recently invented this trick. Dr. Matrix must have learned it from a local conjuror. Can the reader guess the clever modus operandi before I disclose it next month?

"The goblet and the wine never existed," Dr. Matrix said. "They were just illusions." He giggled nonestically. "But

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let me show you something you'll like even better: one of the ancient dances of Kali."

He led us out of his office and down a corridor to a small theater-in-the-round. We seated ourselves in the lowest circle. Dr. Matrix again clapped one hand (we never did figure out how he made the sound), and the bright light was instantly replaced by a dim red glow from concealed bulbs at the ceiling's circumference.

From somewhere came the twangy sound of an Indian *raga* played by native instruments. The beat seemed to get constantly faster, but this was an illusion because it always remained the same. Suddenly Iva appeared on the small stage. Her only costume was a pentagonal mirror on her navel. It glinted and flashed ruby light while her torso swayed back and forth in a sensuous dance of indescribable beauty. In the scarlet light her skin was as black as the skin of Kali.

"Zuleika is topless and bottomless," said Dr. Matrix, "to remind us that we must strip ourselves of all illusions. The world has neither top nor bottom because it doesn't exist."

Sam and I applauded wildly when the dance ended. "Viva illusion!" I shouted as I stepped forward to give Iva a congratulatory hug. My arms passed through thin air. Her image had vanished, although I could hear her giggling nonestically in the distance. It was all a stage trick produced by hidden concave mirrors.

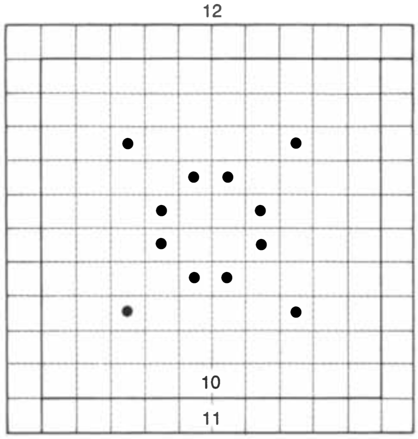
Iva returned to the city with Sam and me, and the three of us had dinner at a Japanese restaurant near the Grand. "Let us eat, drink and be merry," said Sam as we raised our first cocktails, "because nothing is real."

"And because," added Iva, "tomorrow I may diet."

She told us that her father was organizing a major PR campaign for 1977 to promote PM in the U.S. The campaign will be managed by Bagel Lox, a former vice-president of the Dr. Pepper Company. Jerry Rubin, Mrs. and Mr. John Lennon, Doug Henning and Mia Farrow have already visited the Calcutta temple (all expenses paid) and have become enthusiastic converts. John Denver is writing a song about PM called "Don't Worry about What Ain't."

I would have stayed longer in Calcutta if Iva and her father had not planned to leave in a few days for a visit on L. Ron Hubbard's yacht. It had just entered the Bay of Bengal to tie up at Calcutta. Before I left the sad yet somehow beautiful city Iva handed me a folded file card on which she had written my secret mantra.

As my plane climbed above the Nonestic Ocean I ordered a martini and glanced once more at my mantra. *Ohwa—taboo—biam.* My consciousness was being altered by a second cocktail before the meaning hit me. I fancied I could hear Iva giggling, but it was just an auditory illusion.



Solution to last month's problem

Last month's combinatorial problems are answered as follows:

Klondike Puzzle. Sam Loyd's solution is unique if the "troublesome 2" is changed to 1. It is easy to show that any other nonzero digit in this cell provides an alternate escape route. Digits 4, 5, 6, 8 and 9 lead immediately to escape, 3 provides escape in two steps to the southwest and 7 offers escape in two steps due west.

Chinese Checkers. Ten marbles on a Chinese-checkers board can be transferred to the opposite yard in 27 moves:

1. 115–106
2. 120–115–93
3. 116–105–82
4. 82–72
5. 118–105–82–63
6. 121–116–105–82
7. 114–94–71–73–53
8. 53–42
9. 112–114–94–71–73–53–30
10. 119–114–94–71–73–53
11. 106–81–83–62–43–41–18
12. 18–9
13. 113–114
14. 117–106–81–83–62–43–41–18–5
15. 9–8
16. 114–106
17. 106–81–83–62–43–41–18
18. 72–54–52–31–9–2
19. 93–72–54–52–31–9–7
20. 82–72
21. 72–54–52–31–9
22. 42–17–6–4–1
23. 63–42–17–6
24. 53–42
25. 42–17–4
26. 30–10–3
27. 18–10

The solution is palindromic: the second half is a mirror image of the first.

Minimum No-Three-in-Line Problem. The pattern in the illustration above gives a minimum of 12 counters for boards of side 10, 11 and 12.

Remote Control Racer

A new fun leisuretime activity made possible by the new electronics.

Computer logic has added a new fun way to control remote control products.

The Remote Control Racer is a competition scale model race car controlled by a transmitter using computer logic.

Think of it. Remotely drive a model race car from as far as sixty feet—turning left and right, going forward and reverse. It's great fun for hobbiests, children and the whole family.

DIGITALLY PROPORTIONAL CONTROL

The steering is controlled as you control the steering wheel on your remote control unit. Turn the wheel slightly to the right and the car wheels turn slightly to the right. Turn your control fully to the left and the car wheels turn fully to the left.

There is no transmission required to go from forward to reverse as the high quality servo motor simply reverses polarity to change gears. Press the forward lever on your remote unit and you go forward. Press the reverse lever and you go in reverse. It's just that quick.

BUILT TO THE FINEST DETAIL

The camber caster-action front wheels parallel a full-sized car's suspension system and they actually tilt on the turns. An independent floating rear axle maintains positive traction even on rough terrain.

The Remote Racer replaces the gasoline powered remote control race cars that have sold for well over $100 a unit. Remote gas powered models give off odors and are often temperamental. The Remote Racer is quiet so it can be run indoors and it is not dangerous so even children can safely play with it.

The remote control unit (left) controls the race car's electronics (center). The four "C" cell batteries fit in the underside of the Racer.

SOPHISTICATED ELECTRONICS

The sophisticated electronics in the Remote Control Racer consists of 40 transistors. When you operate the control unit, the transmitter generates computer digital logic in a train of digital pulses which then are amplified and transmitted to the racer. The racer then has a sensitive receiver which receives the pulses and in turn translates them into data that eventually translates into power for the car.

The sleek lines of the Remote Control Racer follows the designs of some of the more popular race cars. The car measures 3½"x5"x12".

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You can run as many as six different cars in a race as each car will be on a separate remote control frequency. There are four different colors available, red, white, blue, and yellow and each racer comes equipped with its matching remote control unit.

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The Remote Control Racer is a well built, well engineered electronic instrument with a 90 day limited warranty. JS&A further guarantees your satisfaction—if you are not absolutely satisfied with the value, quality or fun you are having, fine—return your racer within ten days for a full refund. You can't lose.

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BOOKS

The deadly flu epidemic of 1918 and the subtle discipline of lakes

by Philip Morrison

EPIDEMIC AND PEACE: 1918, by Alfred W. Crosby, Jr. Greenwood Press, Westport, Conn. ($17.50). The flu was not even a reportable disease in that spring of 1918. True, there were a lot of cases of the grippe going around, and rather more people died than had been expected. There was certainly something odd about it: in the few postmortems the pathologists did they saw but could not understand an unusual widespread edema and hemorrhage in the lungs. Like the war of that terrible year, this malady preferred young adult victims: the curve of mortality against age was shaped like a *W,* with the central peak between 20 and 30, instead of the familiar *U,* with respiratory death claiming only the very young and the very old.

The epidemic seems to have begun in the U.S. It spread around the world within four months, killing relatively few, but those few were mainly young adults. In May of 1918, 10 percent of the men of the British Grand Fleet at Scapa Flow were down with it. By July the docks of Manila in the Philippines were crippled, with three-fourths of the longshoremen down. Although people called it the Spanish influenza, it had not originated in that neutral country. But the eight million Spanish who fell ill were freely written about, whereas within the belligerent states of Europe and America war censorship minimized the reporting.

It was a pandemic, all right, but a mild one, claiming its dead in the tens of thousands, although there must have been many thousands of brief illnesses for every death. The old physician's saw—"Quite a Godsend! Everybody ill, nobody dying"—did not quite fit this new flu, but no one yet felt the error. American public health was robust; Equitable Life had its best year. But in the midst of the lightly regarded pandemic a new virus had appeared, and "some 1.5 million American adults who were most perfectly qualified to cultivate" it were in the military camps, traveling freely, dispatched across the sea within six months in the fastest migration known up to that time.

The little RNA coils in their spiky protein jackets changed slightly sometime during the latter part of August, 1918. At Brest in France the American Expeditionary Force had its chief port. At Freetown in the British African colony of Sierra Leone troop transports took on coal to break the long haul to British ports from Australia. At Boston the First Naval District played an important, although not a dominant, part in training and shipping Yanks over there. By the end of September the war had flared into the American offensive of the Meuse-Argonne, and the "Spanish influenza" had become deadly. In Sierra Leone one person in 30 of the entire population had died, in Brest there were thousands dead, French and Americans alike, and in Boston there was panic.

As the fall and winter progressed the disease spread from the Aleutians to Calcutta. (By May of 1919 it had ebbed everywhere.) This graphic volume details the American experience, region by region, in camp and on shipboard, and supplies at least a broad narrative for the world as a whole. The October draft call in the U.S. was canceled, although General Pershing wanted more men. Philadelphia was the worst-hit city in the East: of its two million citizens more than 12,000 were dead of the flu and its concomitant pneumonia by the middle of November, against a macabre background of military embalmers and a price-controlled quick-coffin industry.

San Francisco had its turn, forewarned. There the first peak of deaths had passed by the middle of November; the city was hit less hard than the East, and it felt that its civic unity had stopped the flu as once it had flouted the earthquake. In public places most San Franciscans wore the gauze face masks much urged by the authorities. The Armistice arrived like a performance in the theater of the absurd: "Bonfires blazed up on [the] hills, all the whistles and sirens in town let loose.... Many had cow bells,...and everyone, except the infamous slackers, had a mask on. [There were] tens of thousands of deliriously happy, dancing, singing, masked celebrants." Then the flu returned for Christmas, although it was only about half as bad. Masking became an embattled political issue; it meant "the stilling of song in the throats of singers." The proponents of masks were even threatened by a bomb. It appears that masks had no measurable effect; Stockton, Calif., where masking was faithfully practiced, fared no better than Boston, which had taken no control measures.

Dr. Crosby judges the American cities generously. They could do little of value against the flu. No one knew how. The public-health institutions were not at all equal to the challenge. The social structure nonetheless proved itself fit, in spite of inequity, slums and drifters. The flu actually brought to the U.S. a kind of social cohesion: Americans lent one another a helping hand. "When everyone in the nation had a fever and aching muscles or personally knew someone who had, Americans did by and large act as if they were all, if not brothers and sisters, at least cousins."

The terrifying plague infected more than 25 percent of the U.S. population. It seems probable that at least that fraction of the world population was infected. A conservative estimate of the excess of respiratory deaths in the U.S., with the rates of 1915 as a base line, comes to about 550,000 in a period of 10 months. The fatality rate was thus about 2 percent. The usual world figure is 21 million dead, but it is "probably a gross underestimation." That many may well have died on the Indian subcontinent alone; the mortality there in October of 1918 was "without parallel in the history of disease."

Yet the dying does not bulk large in the American mind. It has inspired no awe; the Black Death means more to us—or did until the Fort Dix death early this past spring. Of the six best-selling college textbooks of American history only one even mentions it. Stein, Dos Passos, Fitzgerald, Hemingway and Faulkner barely allude to it. Only Thomas Wolfe and Katherine Anne Porter recognize the killer in his terrible dignity. Porter's *Pale Horse, Pale Rider* is a masterpiece worthy of the flu. The virus nearly killed her, and it did take her love, a young army lieutenant. Dr. Crosby, who has immersed himself in this strange brief period, sees her novella not only as the interior voyage it is but also as "the most accurate depiction of American society in the fall of 1918 in literature."

Why did the flu not mark the minds of the survivors as it filled the graves? Apparently because the catastrophe was almost entirely a statistical one. Nearly everyone who was infected recovered—97 or 98 percent. It took few well-known people, since it killed mainly the young. It was relatively evenhanded with town and country, rich and poor. It is remem-

Questions you should ask and answers you should receive when you are setting up, or re-evaluating your employee savings or profit-sharing plan.

Perhaps we might begin by reminding you that you should look into a number of different plans before committing yourself to any one.

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A. You should for this reason: Suppose your plan has to pay out to employees more than is contributed in a given year? This could occur if there are an unusual number of early retirements or if a plant closes. *Regardless of what happens, Metropolitan guarantees the principal to your participants.*

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Where the future is now

bered not by the collectivities of society, not by journalists, historians or lawgivers but by the atoms of society: individuals. The letters and journals of ordinary people are full of it, and those who lived through it still acknowledge it. The fourth horseman struck freely but at random; anyone who tries to give a logical account of the past is compelled to ignore his blows. "How does one discern the great figures of the mid-twentieth century who never became great because they died of flu in 1918?" Only the rare artist such as Katherine Anne Porter speaks what is silent in the hearts of millions.

The Polynesians, isolated from most infections by the enfolding ocean, suffered worst of all wherever the flu reached. Western Samoa, freshly under New Zealand rule, received no warning. No one radioed from Auckland, where the disease raged, to explain that the ship *Talune* had sailed under quarantine, and her captain did not remind the medical officer on her reaching Apia. Between the arrival of the ship on November 7, 1918, and the end of the year about 20 percent of the Western Samoans died of the flu and its complications. Many of the sick were taken simply by starvation; they had no one to feed or tend them. Fortunately in American Samoa, Commander Poyer, the naval governor, was a man able to draw conclusions from the daily wireless news. He turned back even the mail boat from Western Samoa (which caused the New Zealand officials to break off radio contact with their American counterparts). It is only 40 miles between the two islands, but Poyer called for every Samoan leader to prevent the landing of any boats from the west. The local people created an effective coast patrol of their own. The virus never reached American Samoa. By early 1919 men in Western Samoa would sing, to the tune of "The Star-spangled Banner," a Polynesian lyric that goes in translation: "In Upolu, the island of New Zealand, many are dead / While in Tutuila, the American island, not a one is dead.... God in heaven bless the American Governor and Flag." Crosby drily adds, "The like would not be heard again in a colony."

How did the virulent pandemic come about? We do not yet know. Even the molecular virologists, the masters of nucleic acids, cannot say. Indeed, Crosby does not mention RNA. He describes virology from the work of the 1930's, which found the virus, to about 1960. For a virus to be virulent against young adults may be a sign that the generalized immune system of the child has been replaced by a vigorous response to local injury. When the virus spreads over the entire surface of the lungs, the adult response is a massive inflammation; the lungs are overwhelmed by the exuded fluid. Older people react with less vigor locally, and they survive better. But why was the virus so deadly overall? In 1957 a different antigenic strain of the flu pandemic struck out of Asia even more widely. Its world mortality, however, was well under one per 1,000 cases. We have little idea why.

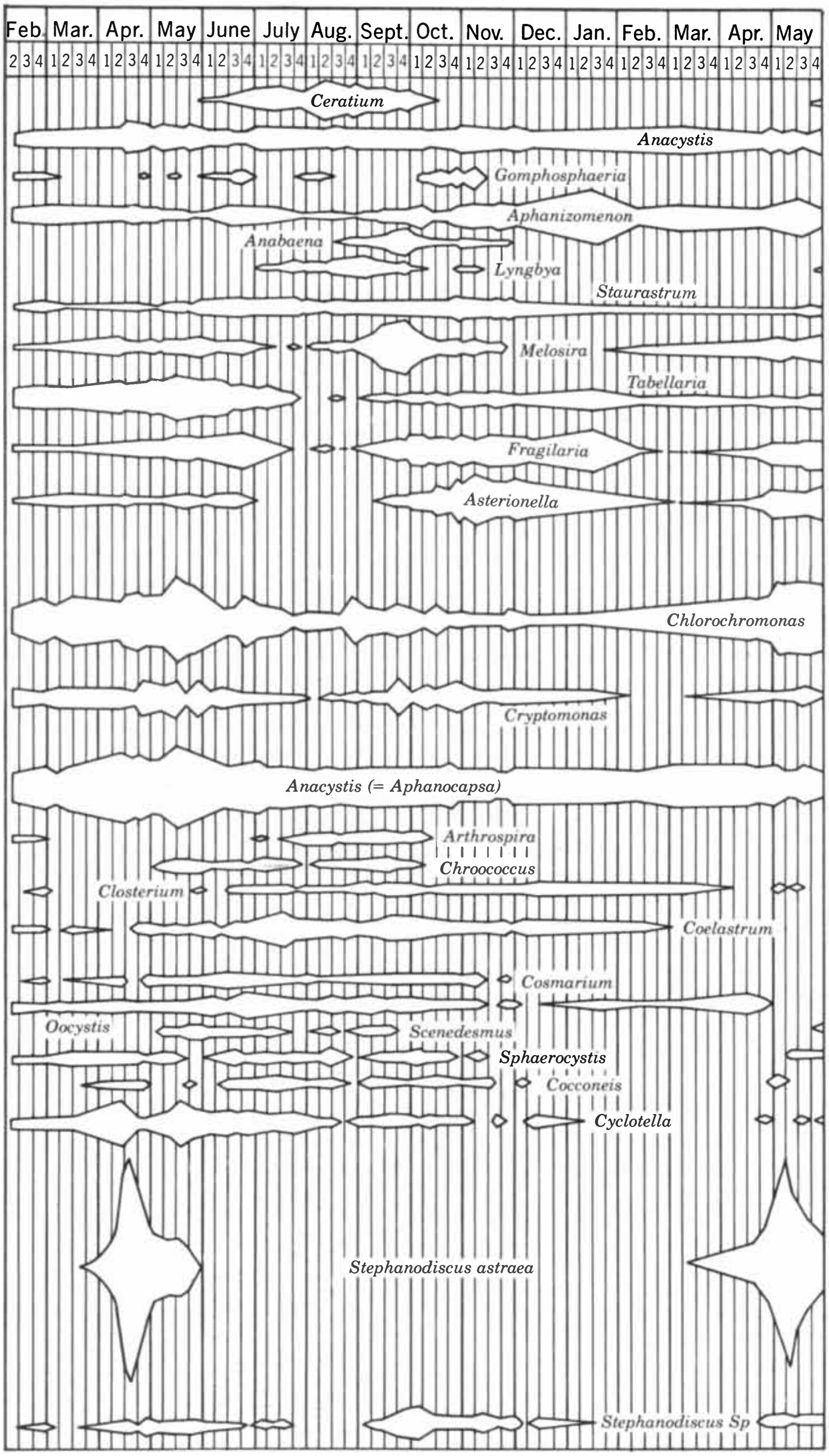
There is one theory, not flawless and not favored today but nonetheless plausible and fruitful. J. S. Koen, a U.S. Government inspector, saw a raging epizootic at the Cedar Rapids Swine Show in October of 1918. The hogs had a new disease: sore muscles and drippy snouts, with much mortality. Koen wrote: "It looked like flu, it presented the identical symptoms of flu, it terminated like flu, and until proved it was not flu, I shall stand by that diagnosis." Ten years later Richard E. Shope, an Iowa virologist at the Rockefeller Institute, took it up. Shope worked for 20 years on the swine flu. He argued that it was a virus infection on top of an endemic respiratory infection of swine caused by a bacterium known as Pfeiffer's bacillus. The flu virus remains latent, like the virus of the fever blister, until it is triggered by cold, wet weather. Then the twice-infected swine show deadly symptoms.

That explains the timing of the epizootic, which occurs only in the fall and the winter. The hog disease explodes without spreading; since its agents are already in place, it is everywhere at once. For Shope the human flu of the spring of 1918 seeded the new virus infection. Then a bacillus—found in most autopsies of victims, and long known as *Haemophilus influenzae*—caused the later pandemic under the stress of bad weather. The trouble with the hypothesis is that the virulent wave started in August, in the hot port of Freetown. Some victims of the Spanish flu had no bacilli in their lungs or throat, and laboratory animals got the flu from the virus alone. But perhaps there is some other form of prepandemic seeding. The flu peaked in Boston and in Bombay in the same week of 1918. Is something latent?

Those six cases at Fort Dix early this year showed the old "footprint in the blood": antigens like those against the swine virus, which are usually found only in people old enough to have had the 1918 flu. The virus itself is still unknown to us. In 1951 some 1918 victims were exhumed on the coast of Alaska in the hope of finding living virus preserved in the icy graves, but it did not appear, even though it was possible to culture some living bacteria from the dead tissues.

Why was the Spanish flu so deadly? Will it come back in some form even to our world of egg-reared vaccines? This winter or the next is likely to make us all somewhat wiser, even though we cannot expect full knowledge. The ecology of pathogenic organisms is a fateful and difficult subject.

A TREATISE ON LIMNOLOGY: VOL. I, PART 1, GEOGRAPHY AND PHYSICS OF LAKES, PART 2, CHEMISTRY OF LAKES; VOL. II, INTRODUCTION TO LAKE BIOLOGY AND THE LIMNOPLANKTON; VOL. III, LIMNOLOGICAL BOTANY, by G. Evelyn Hutchinson. John Wiley & Sons (Vol. I, Part 1, $11.50, Part 2, $10.50; Vol. II, $61; Vol. III, $30). Professor Hutchinson, the Yale ecologist, is so rightly dis-



Seasonal variation of plant plankton in Lake Mendota, from **A Treatise on Limnology** tinguished for the breadth of his learning and the elegance of his expression that it might seem unnecessary to call attention to the compendious technical work with which he has been seized for 20 years and more. This notice to the general scientific reader, one far from the branch of ecology for which these three kilopages form a rich and growing resource, is made timely, however, by the circumstances of publication. The initial volume of the treatise, first issued in 1957, has been brought out again within the past year in two inexpensive paperbound parts, and a third volume (cut in scope to save cost and time) has just been published. More volumes are to come, treating of the entire biological productivity of lakes and of their "typological, stratigraphic, and developmental aspects, [of] the lake as a repository, if not a mirror, of human history." No brief general review can sample this grand treatise in a representative way, but it is worth dipping the net here and there to encourage a wider attention to the topic, growing each year in salience.

Lakes seem on a human time scale "permanent features of landscapes, but they are geologically transitory, usually born of catastrophes, to mature and to die quietly and imperceptibly." Scale and fluidity determine. In an ordinary road map Lake Erie would be about the size of this page, and on that scale its waters are about the thickness of the page. The basin of a lake, usually a minor feature of the topography, can form in a wild variety of ways: 76 types of lake origin are described with examples and discussion, including lakes born of volcanoes, of meteorites, of wind and of ice. Our own active postglacial epoch is particularly rich in lakes, and in it lakes are also created by two mammals: the American beaver and man. Our imposing Great Lakes are ephemeral; only rift lakes such as Lake Baikal in Siberia and the lakes of East Africa and such cutoff ocean basins as the Caspian Sea can claim longevity in geological terms. Their life forms testify to respectable spans of evolutionary time.

Lakes are of many shapes and sizes, here some strung like the beads on a rosary (the mapped example is in Montana) and there one with 40 percent of its surface area in islands (the example is in Ireland). There are volcanic caldera lakes, deep for their size, but there is no lake as deep as the nearly two kilometers of Baikal. Many bottomless lakes exist in legend; a hermit once lived, so Hutchinson was assured, on the shore of Lake Manasbal in Kashmir "devoting his life to cording a rope with which to sound the lake." Although in the fullness of time he felt that his task was finished, he could detect no bottom once he had paid out his life's twisting, and so "he threw himself after the rope and was never seen again." The measured maximum depth of that lake is 12.7 meters.

The motions, water budget and optical and thermal properties of lakes are treated in some detail, with the main equations not slighted (although only the results appear and not the specialized derivations). The hydromechanics is "inevitably out of date" but still broadly of interest. The somehow Edwardian subject of seiches—the resonant sloshing of a lake driven by wind and barometric changes, as coffee sloshes when you gently tip the cup—is handled in detail, with a list of resonant periods, including the period of the coffee cup (put at three or four cycles per second by the model developed for lakes). It is not easy to spot the small true tides among the seiche jiggles, although some rough fits in the biggest lakes are plausible. At Duluth the range of the tides is about an inch. At the David Taylor Model Basin near Washington the fit is pretty neat: the range in that half-mile man-made pond is almost a tenth of a millimeter.

The warm top layer of Temperate Zone lakes deserves and gets careful discussion. The stratification and mixing cycles that depend on the high density of water at four degrees Celsius below that layer are fundamental to the climate of the lake's internal world. Some deep lakes do warm up a little at the bottom; such an inversion can be due to the flow of heat from the earth, from the metabolism of organisms and from warmer surface water that has acquired solute from the lake until it is "sufficiently dense to move downward" but "sufficiently warm to convey heat into the deep parts of the basin." Ice is not forgotten; it is impressive to learn that the large cracks in Baikal's ice are constant enough from year to year to have received place-names of their own.

The second part of the first volume treats of chemical cycles, beginning with rainwater (with sea salt and sulfates from smokestacks dominating its solute chemistry) and going on to oxygen, carbon dioxide and the ions of water: phosphorus, silica, nitrogen and the less important trace constituents. These chapters are well done; they predate and prefigure modern concerns with detergent phosphates and other contaminants.

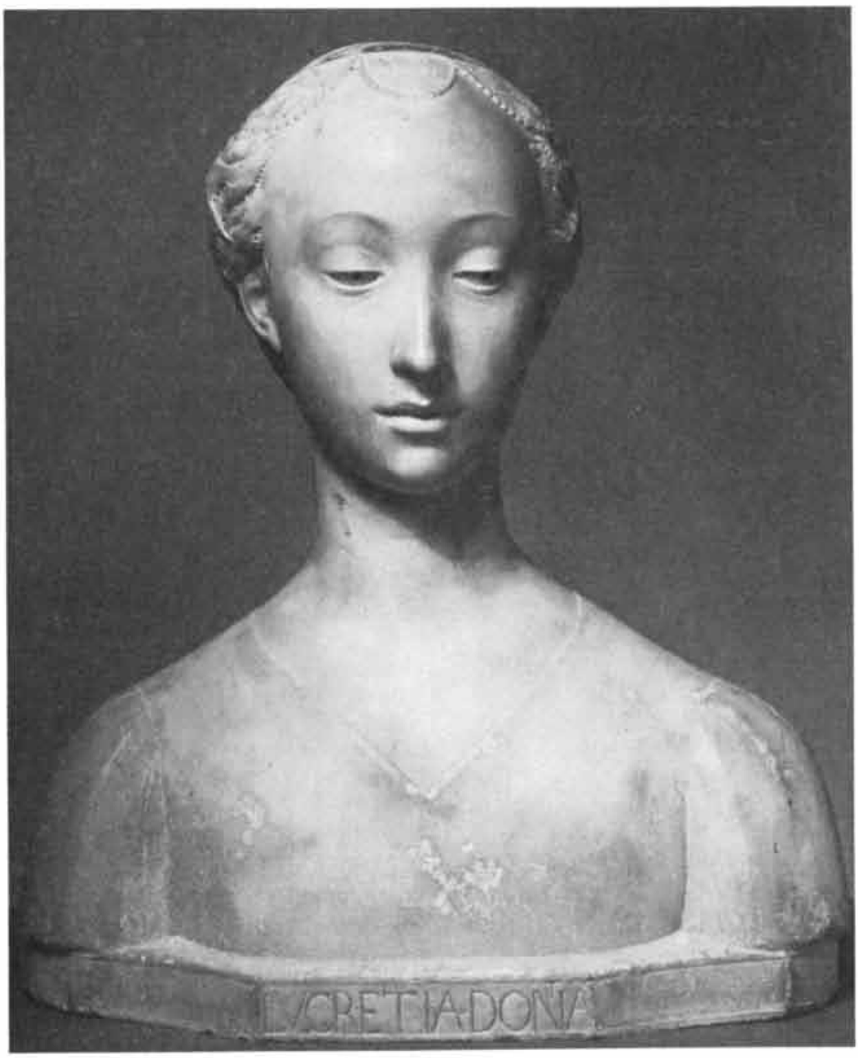
Volume II opens with a remarkable set piece, written a decade ago but as fresh as the current journals, that devotes 200 pages to an overall survey of freshwater life, from the plankton-eating flamingo to the Baikal seal. (The promised full treatment of the Baikal biota is still to come.) Here is the smallest flowering plant, two-thirds of a millimeter long, first described in the Mato Grosso. In the same locality grew the biggest water lily, its floating circular leaves two meters across. ("To d'Orbigny it was the most beautiful known

plant.") Its crimson-centered creamy white flower is warmed by metabolic heat that helps to disperse its heavy perfume. Of the juxtaposition between the smallest plant and the largest one naturalist wrote in 1849: "Singulière bizarrerie de la nature d'avoir semé ensemble ces deux végétaux."

The perceptions of this long essay are congenial to much of the work done since on the origin of life, on prokaryotes and eukaryotes, on the fossil colonies of the blue-green algae. Our freshwater philosopher remarks: "It is tempting to speculate that the oldest complete organism may have lived at the bottom of very shallow bodies of water, or on rock surfaces kept moist by trickling water or spray, under conditions of moderate and variable salinity. Life surely began in water, but there is no evidence it began in the sea." The rest of the second volume treats the freshwater plankton quite fully, from the Reynolds numbers associated with the bristly forms to the dance of the water flea *Daphnia* (to and fro along the axis of a red light beam but crosswise when the beam is blue!).

The third volume goes on to deal in even more taxonomic detail with the larger freshwater plants. The texture of the material will be suggested by the fact that three pages in nearly 600 are devoted to the epiphytic plants that grow on the mossback snapping turtle. This overgrowth may break the hard outline of the alligator snapper, which fishes by "remaining quiet with its mouth open, wiggling its tongue as a bait."

The chronicle of the adventitious spread of certain water plants is a high point. The aquatic herb *Elodea canadensis* reached Ireland and Britain in as many as five separate introductions by 1840. Within a decade it had spread from the river Cam (a hapless botanist almost certainly set them out in the new botanic gardens within easy reach of the river) to clog the canals of the entire Fenland. Barge traffic was then central to British commerce, and the shippers had to put on extra horses. Thereafter



Giovanni Bastianini's 19th-century forgery of a Renaissance bust, from **Authenticity in Art**

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the *Elodea* population declined even faster than that of horse-drawn barges. The range of the plant now includes all of the north Eurasian landmass. Almost all the flowers are female, never setting seed; the plants may well descend vegetatively from the clone found in a Leicestershire canal lock in 1847. What stabilized this once pestiferous population is not known.

The water hyacinth, with its showy violet-blue flowers, is native to fresh waters east of the Andes. In 1894 it was placed in private pools in Java, and about 10 years later the same was done near New Orleans. It is now a serious pest over the entire wet warm world, from Virginia to Australia. Airborne man spreads water plants faster than the wind or birds ever did.

The burden of these books is plain, and it is fascinating. Each lake is a member of a large genus. No two of them are alike, but they are numerous and similar enough to suggest the general laws of their being. They are little worlds condensed in space, so that a meter of depth is as important as a kilometer of mountain slope. They are even more compressed in time; their entire geologic history belongs to the Recent, and one year's cycle may be as significant to the succession of living species within a lake as a glacial epoch is to a wide prairie. Professor Hutchinson brings us this natural history with brilliance and devotion, ranging from eddy viscosity to the look of white blossoms on a sky-reflecting brook. We eagerly await the rest of the feast.

This work of reference and pleasure, with its masterful grasp and wide horizons, is presented serviceably enough, and the paperback editions are a welcome innovation. The books lack, however, the generous apparatus they deserve: large pages, clear footnotes and eye-pleasing typography.

Authenticity in Art: The Scientific Detection of Forgery, by Stuart J. Fleming. Crane, Russak & Co., Inc. ($14.50). As long as works of art have been esteemed they have been forged. The first line of defense against such knavery is the knowing eye, now sharpened and trained by the meticulous scholarly studies of art historians. But that eye has its blind spot. Stylistic mistakes that conform to contemporary taste tend to pass unnoticed. It is unrealistic to hope to discover what we now accept unconsciously, but the first plate in this agreeable and expert book strikes home. The marble bust in it passed as high Quattrocento style when it was carved about a century ago by Giovanni Bastianini of Fiesole. That productive Tuscan sculptor and his unscrupulous dealer with a soft sell placed fake Renaissance works on the market for 20 years. It is not hard for us to see in the sentimentality and overdelicacy of the features of Lucrezia Donati the identity of the piece as an "outstanding example of Italian art of the last century." But expert contemporaries at the Louvre and the Victoria and Albert Museum welcomed such works as old masterpieces.

Of course, a clever expert can spot objective flaws such as errors in painted costume. Artists usually paint clothing more accurately than they realize; a splendid forgery shown here—a false Vermeer by the peerless Han van Meegeren—shows sleeves cut on the bias. In our time of power machinery that suggests tailoring simplicity, but in the 17th century such a waste of expensive cloth would have been avoided by any tailor for economy's sake.

Materials science to the rescue! Specific works of art are never mere image and form; they are embodied in matter. That matter must bear marks of the method and the epoch of manufacture. The author is an acute Oxford physicist who has become a leader in this novel specialty. He offers methods old and new for the study of paintings, ceramics and metals, presented at a level suited for the general scientific reader and the student of art. The book is also an introduction, even for the expert, to the fascinating scattered literature, old and new.

One first looks at the surface. Even dealers now use the simple ultraviolet lamp, which shows fluorescence, a surface property quite sensitive to details of surface treatment, such as erasures and naïve restoration. The notorious Vinland map at Yale did not pass this test: the map ink did not quench the glow of the vellum as old inks would have. When the 20th-century pigment titanium dioxide showed up as well, the map was repudiated. Careful forgers in Japan today "conscientiously spray" their efforts in porcelain and early bronzes with a nonfluorescent material.

The microscope also helps in the detection of forgery; a thin sounding of a painting made with a hypodermic needle can reveal a great deal. X-ray and infrared examination peels away the layers of paint visually, revealing underlayers that may disclose the artist's honest travail or something quite different. The X-ray plate shows the heavy metal atoms in background pigments; infrared reflectography displays the undersketching done in black chalk or charcoal. Chalk once consisted of natural microfossils, but since the middle of the 19th century it has mainly been artificial. Pigments have changed too; a careful chronology of the succession of seven popular blue pigments helps to establish anachronisms, although caution is necessary. After detailed study a famous Rubens at the National Gallery got "a clean bill of health," even though some varnish containing synthetic ultramarine—at least a century out of period—had been demonstrated. Few Old Masters survive without retouching here and there; in the end the curators could breathe easily again.

Wood frames and panels are not too hard to date by tree-ring study, but good forgers begin with authentically old wood. Subtler clues are worth following; neutron activation, mass spectrometry and autoradiography search out trace elements and isotope ratios even in materials chosen as being chemically in period. For example, almost all linseed and other drying oils one can now find have perforce been prepared since the radioactive-fallout increase of the 1950's; such vehicles for pigment simply do not last longer on the shelf. Old prefallout pigments are not as hard to get, but high carbon-14 activity would mark the new vehicle, given 100 milligrams of dried paint to count.

The author has been a pioneer in the application of thermoluminescence to the dating of ceramics. This half-magical art depends on the partial storage within the quartz and feldspar grains of energy internally released by natural radioactivity and cosmic rays. Some of the electrons set free by the ionizing particles are trapped at imperfections in the crystal lattice of the grains; a carefully controlled temperature rise releases them to emit measurable visible photons as they seek their ground state. The method can date most pots to within about 15 percent for ages upward of 500 years. If a dose of radiation is artificially administered to the sample, certain unstable traps can also be estimated, and the method can be extended to pieces only 50 years old or even younger.

Greek, Chinese, Florentine and Etruscan terra-cottas are splendidly forged today, sometimes with the authentic ancient piece molds—not so much a forgery as a new edition. Here the forger and the investigator alike are virtuosi. The technique has posthumously shown up Charles Dawson, the man who is most strongly suspected of having produced the discredited Piltdown jawbone. Dawson had earlier found certain exciting "Roman" tiles, now safely dated to the Edwardian years of the presentation of his "discovery" in London. (This seems finally to exonerate the young Teilhard de Chardin, the only other archaeologist who worked the Piltdown site.)

Metals can be analyzed from very small scratch samples or even from the untouched original surface. One uses neutrons and the gamma-ray activities they induce, or X-ray fluorescence under scanning electron beams. Coins have a rich and complex history; fakers and counterfeiters are as old as coinage itself. Henry I of England accepted charges of debasement made against his moneyers in the lean years around 1124. It was asserted that they had used tin to debase the silver coins of his realm; the king summoned them all to Winchester at Christmas and had their right hand and their testicles cut off. We now know through the analysis of the coins made by Henry's coiners that they were innocent; the charges were rumor.

The final entry in the bibliography tells a story in itself. In 1954 one H. F. Whitworth described a fake fossil, "the insertion of an insect's wing into a crystal of selenite." This intricate, fascinating and well-illustrated book is a source of pride for physicists: the author is one, the humorous, instructive preface is the work of the codiscoverer of the spin of the electron, the physicist-connoisseur S. A. Goudsmit, and the book was first published in Britain by the Institute of Physics.

A 16th-century woodcut of amaranth, from **Herbal**

HERBAL, by Joseph Wood Krutch. David R. Godine, Boston ($27.50). The untiring compiler Pliny and his contemporary the Greek physician Pedanius Dioscorides left texts describing about 1,000 species of plants. Most of these were reported as *materia medica*, sources of healing. As Galen dominated medieval medicine, so Dioscorides' manual came to rule pharmacology. (Charlemagne knew a little more: he held that an herb was "the friend of physicians and the praise of cooks.")

What we see here in a visually striking book is a set of more than 100 woodcuts (the beaver, the hare, the bee and a couple of other animal drug sources have crept in among the herbs) clearly reproduced at nine-by-12-inch size from the big Latin folio published by Pierandrea Mattioli in the 1550's. His purpose in the time of Columbus, Copernicus and Vesalius was to help physicians make use of their classical legacy, and he titled his work *Commentaries on the Six Books of Dioscorides.* His book was widely popular, appearing in many languages right through the 18th century.

Mattioli was modest; many of the plants in the book were from the New World, unknown to his Greek model: maize, capsicum and prickly pear, for instance. It is clear that he and his shadowy artists were fully engaged men of their own questing times; the plants are not drawn as copies of copies of the rather symbolic ancient representations but begin to be suffused with the look of nature. Like Vesalius, these men were coming to see for themselves. A century later Robert Hooke of the Royal Society would explicitly claim to "record the thing itself as it appears."

The text of the present book is not at all a translation, not even the titles on the plates. Instead the American critic-naturalist Joseph Wood Krutch has prepared a gracefully written commentary as a facing page for each plate, drawing more heavily on Pliny than on anyone else. He is much less concerned with modern botany than with classical doctrines. So the pendulum swings; for many such as Krutch the "grimmer science of our own day" has less charm than the former reputation of lettuce as a powerful remedy. (Galen thought it worked splendidly for insomnia: "I have found no better remedy than eating Lettuce in the evening.")

Of course, it is wrong to regard the long tradition of the herbalists as all charlatanry and quaintness, commonplace as both ingredients admittedly are. These works are tributaries to the river of science; we denigrate them at our peril, and the late Dr. Krutch (who first brought the book out a decade ago) was riding a cresting wave of opinion. He finds his herbalists "more likely than the modern scientist to impart a sense of beauty and wonder—both of which the scientist may feel, but considers it no part of his function to communicate." Krutch's comments on the kermes oak, the prickly pear, the banana and the date palm are closer to economic botany than to classical pharmacology and are well worth seeking out. The book is certainly a bargain in paperback.

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Several months ago we started our Tricentennial Program by asking for your thoughts on life in America by the year 2076. Instead of a lot of ideas about space ships and robots of the future most of the more than 50,000 responses we've received have been about people's visions of our future as a nation.

The main point that came through, letter after letter, was that most people believe a lot of the things that made America what it is today will shape our future as well.

An overwhelming number of you – ninety-one percent – told us you want the family to remain our basic social unit.

Sixty-two percent feel the nation will be better off when there is no racial, sexual, or religious discrimination.

Seventy-three percent of you told us you expect a reaffirmation of religion and faith by the time of our Tricentennial.

There is a strong desire – almost two-thirds – for more individual participation in government through better communication.

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What's better than statistics is the feeling that the majority of people believe that life in the future can be better than it is today. But we've always been like that. It's what's been called the American Dream.

You've shown us that the future of America lies not in the land or the technologies we master but in the hearts and minds of the people, our greatest resource.

We didn't intend to do a scientific survey but your responses show significant insight into the problems and opportunities that face our nation. We plan to make those thoughts available in a book reflecting many of the interesting letters we've received.

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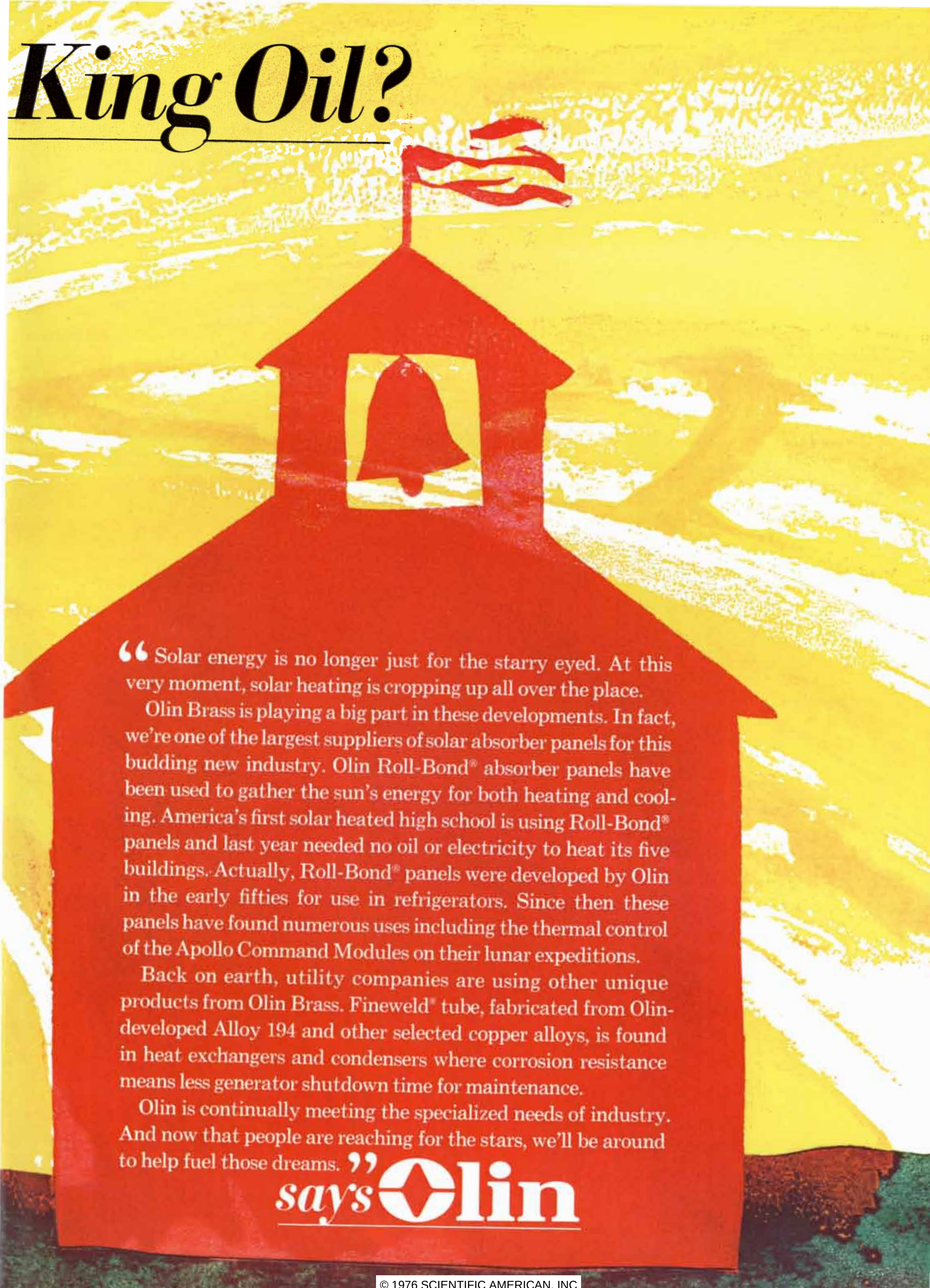

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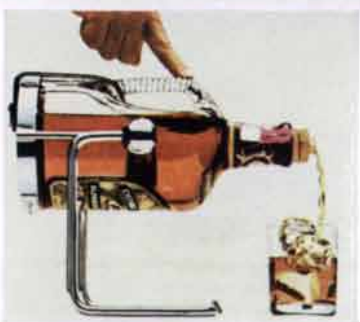

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