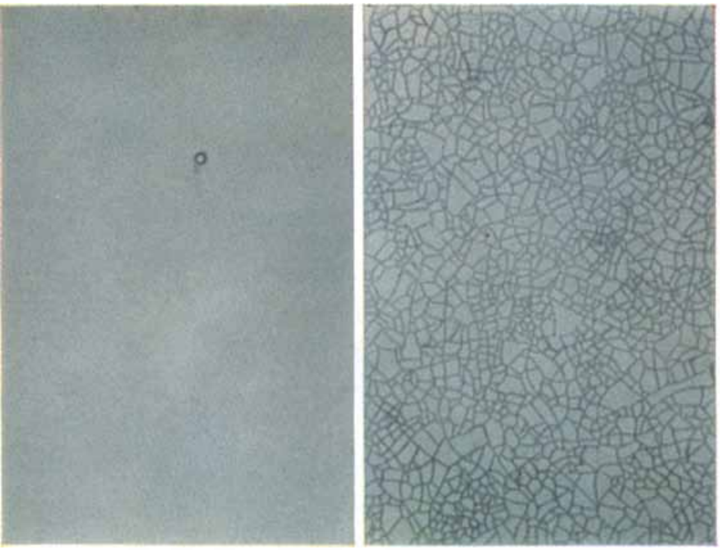
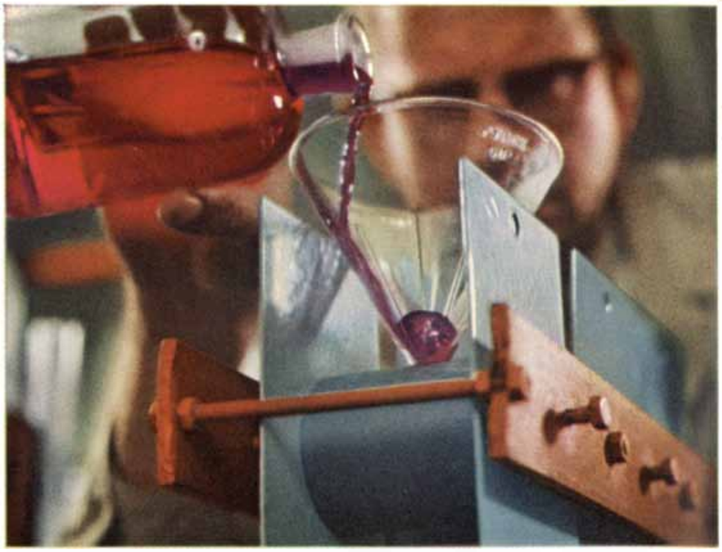
SCIENTIFIC AMERICAN

BUBBLE-CHAMBER TRACKS

SIXTY CENTS

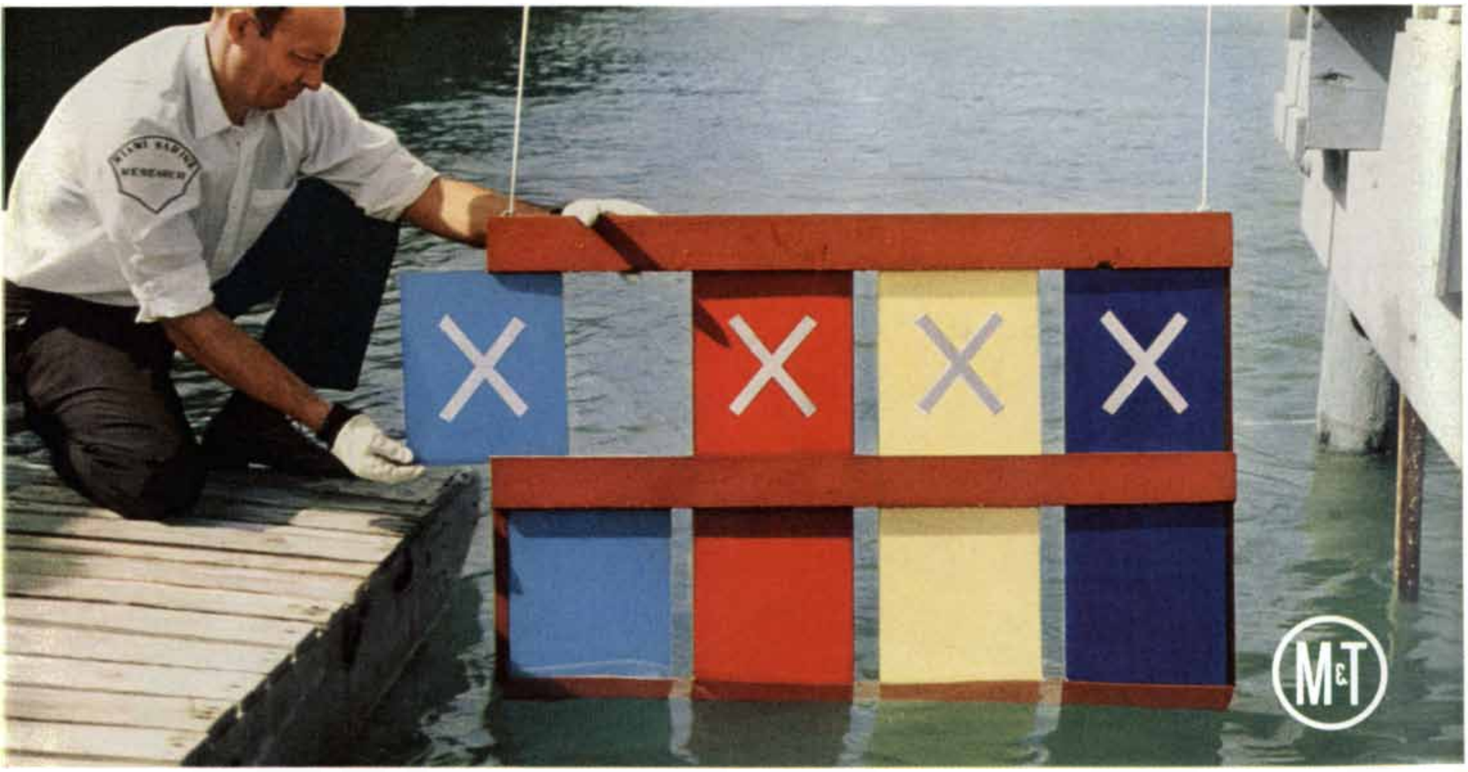
February 1964





Which plated panel resists corrosion better? The panel at the left is a 400 x magnification of ordinary chromium plate. If too thin, the plate has pores and discontinuities. Too thick, it develops gross cracks. With a new M&T plating process, microscopic cracking (right panel) is produced during the plating process. These micro-cracks disperse the galvanic action that causes corrosion on parts exposed outdoors or to other humid conditions.

Corrosion at the interface: Corrosion is usually most severe at the interface between the liquid and vapor phases of a chemically active product. That's why the M&T Coatings Division research laboratory uses special test cells. These are partially filled with chemical solutions. Test panels coated with M&T vinyl finishes are fastened to the sides of the cells. That way, the coatings get exposed to all three: liquid, vapor and interface.



Problem: eliminate fouling without inviting corrosion. Copper oxide-based paints have been used for years to protect ship hulls against marine fouling. But, a copper-based paint on a metal hull quickly initiates galvanic action that causes corrosive damage. Now tidal-water tests with painted metal panels confirm what many boat owners know. With marine paint containing bioMeT* organotin anti-foulant, there's no corrosion due to the anti-fouling agent, and no fouling, either.

*Trademark of M&T Chemicals Inc.

M&T works with chemical and physical properties, such as corrosion resistance, in many materials. M&T capabilities in chemistry, ceramics, plating, organic coatings, minerals and welding may help solve your problems. Write M&T Chemicals Inc., General Offices: Rahway, N. J.

M&T Chemicals Inc.

IN CANADA: M&T PRODUCTS OF CANADA LTD.

Flexible idea for
handling temperatures
up to 3000°C

SYLVANIA DOES EXOTIC THINGS WITH EXOTIC METALS

Our knitted tungsten wouldn't make a very good pair of mittens. But for handling wide variations of temperature in electric furnaces, this closely woven mesh of tungsten wire is just the material to use.

A new development of Sylvania's metallurgical research, "knitted" tungsten solves the problem of thermal-shock damage to expensive furnace elements. Unlike solid materials, tungsten mesh expands and contracts, as temperature goes up and down, without permanently changing shape. As a result, furnace elements now have 3 to 4 times longer life than ever before possible.

Awarded first prize by the American Society for Metals in its competition for "unique product of 1963 among all non-ferrous materials," tungsten mesh is a dramatic result of Sylvania's creative imagination, broad knowledge and extensive experience in the field of refractory metals.

Sylvania knows refractory metals as only a specialist can. And is a recognized leader in the research, development and manufacture not only of tungsten and molybdenum, but of chemicals, phosphors and semiconductor materials as well. To extend that leadership even farther, Sylvania is now at work on many advanced developments in all these important areas. Chemical & Metallurgical Division, Sylvania Electric Products Inc., Towanda, Pennsylvania.

SYLVANIA

SUBSIDIARY OF
GENERAL TELEPHONE & ELECTRONICS

Established 1845 **SCIENTIFIC AMERICAN** February 1964 Volume 210 Number 2

ARTICLES

DEPARTMENTS

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THE COVER

The photograph on the cover is a view inside the 72-inch hydrogen bubble chamber at the Lawrence Radiation Laboratory of the University of California at Berkeley. The long tracks crossing the picture from bottom to top were made by negative K mesons with an energy of nearly three billion electron volts. The mesons were generated by the Bevatron: the Berkeley proton synchrotron. A magnetic field around the chamber bends negative particles to the right and positive particles to the left. The fan of tracks to the left of center is a "four-prong" event caused by the collision of a K meson with a proton. The large spiral track was made by an electron knocked out of a hydrogen atom. The ribbed structure at the bottom of the chamber consists of silvered plastic strips designed to keep stray light out of the lenses of the three stereographic cameras aimed into the chamber. To make this photograph the staff of the Radiation Laboratory slit color film to the 47-millimeter size used in the cameras.

THE ILLUSTRATIONS

Cover photograph by Jon Brenneis
and Lawrence Radiation Laboratory, University of California

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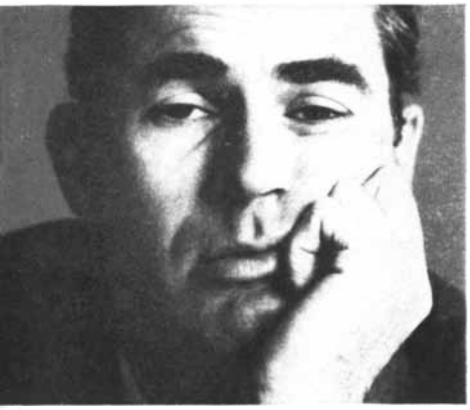
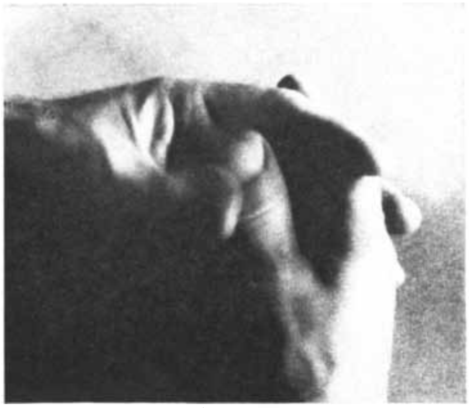
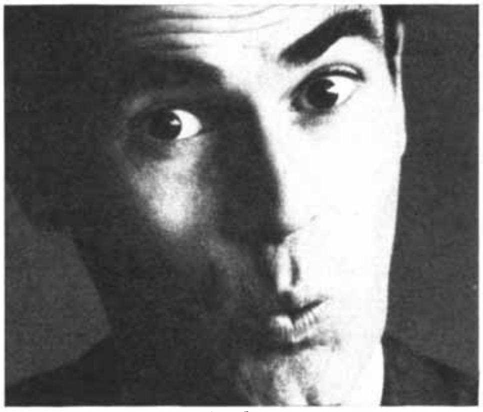
Xerox cures these common symptoms of high engineering costs.

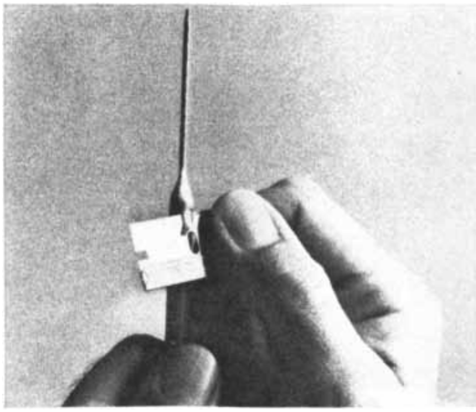

daydreaming


thumb twiddling

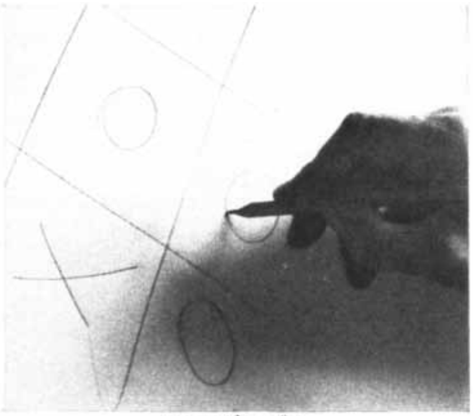

whistling


watering


touring


whittling


chit-chatting


arts and crafts


etc.

Engineers would rather work. But they have to wait for prints. 15 minutes a print. A half hour. An hour. Sometimes longer. And how much does a print cost when you add in the salary of the man who had to wait for it?

If you pay an engineer $8,000 a year, that's 6⅔¢ a minute for each working eight-hour day. If he has to wait 15 minutes for a print, it costs $1.00 worth of his time. For nothing.

Now you can cut this costly waiting time down to minutes. Or less. You need microfilm aperture cards and a Xerox 1824 Printer. And you don't have to buy the 1824 Printer. We'll lend it to you. You pay only for the prints you make based on a minimum number of prints per month. And there are no sensitized papers to buy. The 1824 uses ordinary paper or vellum or offset master stock. The 1824 makes dry, ready-to-use prints that you can make notes or draw on. And it makes prints from all forms of microfilm.

With the Xerox 1824 Printer and unitized microfilm your engineering drawing reproduction system costs less. Ask your Xerox representative for proof.

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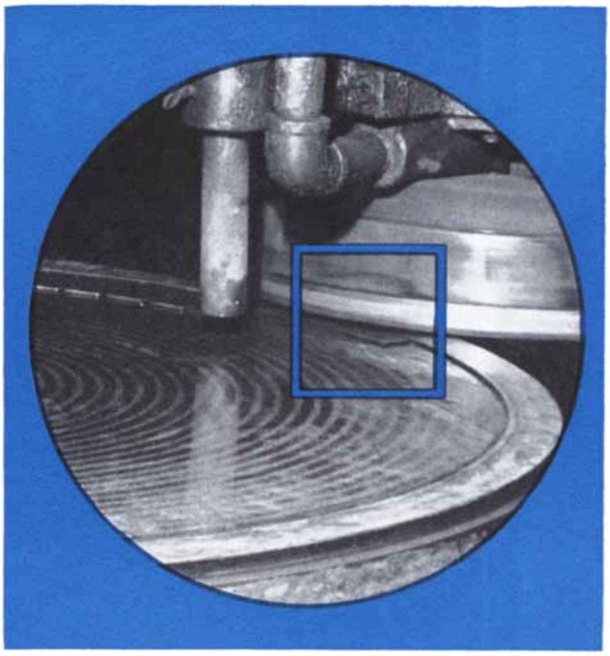
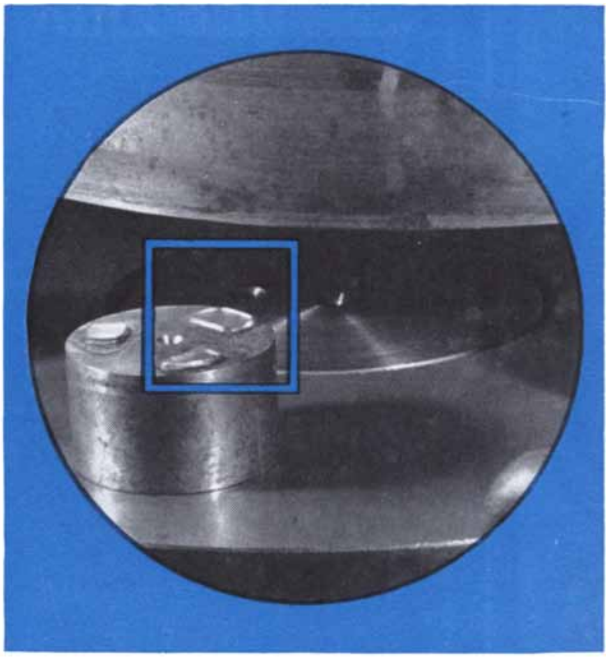
XEROX

XEROX 1824 IS A TRADEMARK OF XEROX CORPORATION.

Each of these jobs is done better with diamonds



GRINDING TITANIUM CARBIDE insert blanks at Willey's Carbide Tool Co., Detroit, is done on Blanchard grinder with 18-inch horizontal wheel containing ¼ inch of 120-mesh diamond grit. The wheel revolves at 750 rpm. The blanks themselves are held to the base of the grinder magnetically.



DOUBLE-FACE LAPPING of ruby laser rod is done on optical-lens polishing machines using diamond compounds from 6 to ¼ micron. Super-smooth finish on rods, made by Korad Corp., Santa Monica, Calif., is essential to their function in producing coherent light beam of energy. Only diamond compounds can achieve this finish without flaws or strains.

INDUSTRIAL DIAMONDS CUT PRACTICALLY EVERYTHING . . . ESPECIALLY YOUR PRODUCTION COSTS

Take 175 computer systems specialists, 90 systems integration specialists, 51 specialists, 65 astro-tracker systems specialists, 15 human factors specialists, 52 attitude control specialists, 92 inertial systems specialists, 85 systems

Not enough.

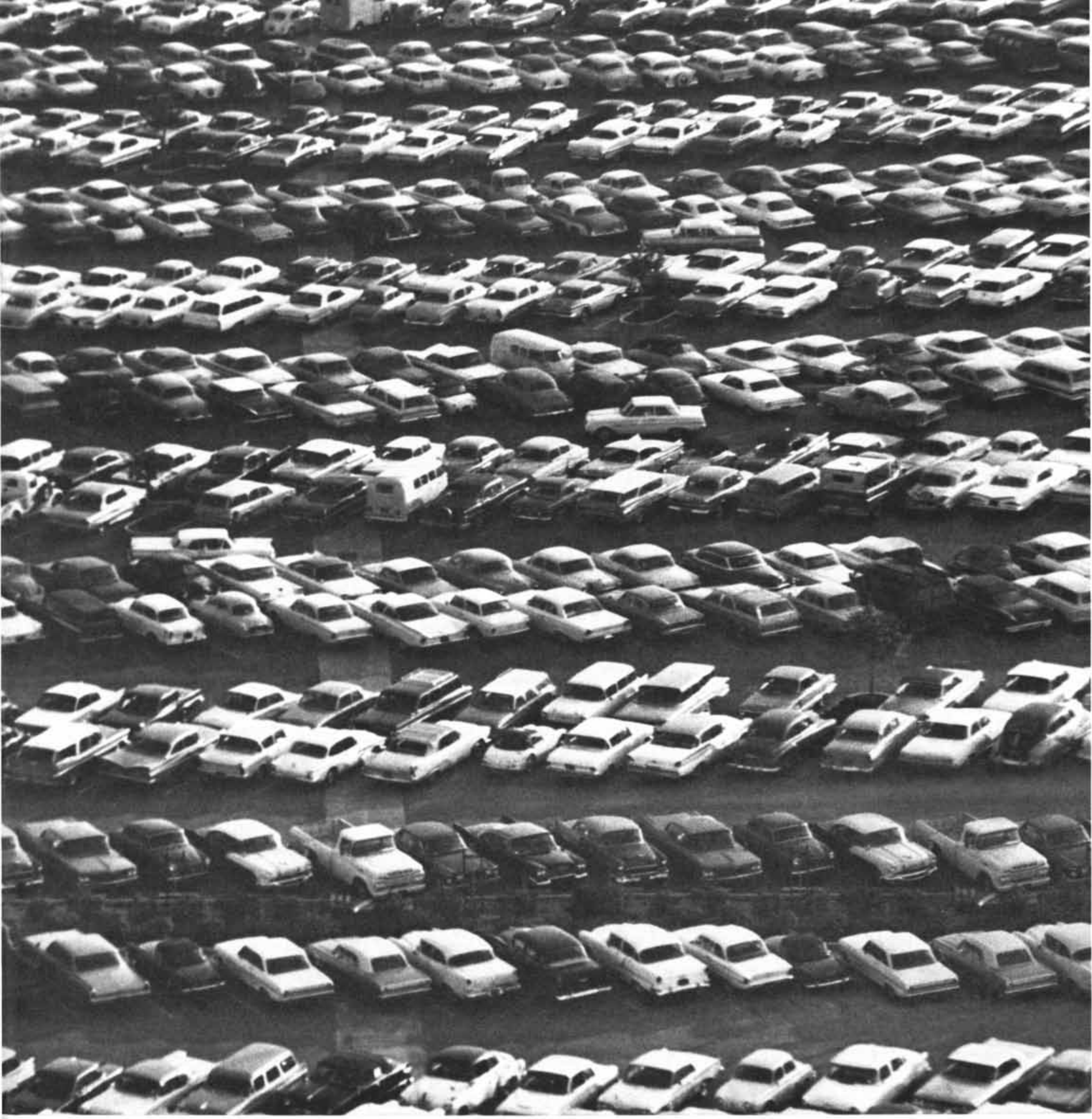
It isn't difficult to assemble an array of engineering talent. Mere money can accomplish that.

The ability to manage these talents and integrate them into a smoothly functioning systems team is not so easily come by.

It calls for technical managers who are imaginative, inventive, and tempered by years of experience in working with their specialist groups.

It calls for the type of management approach that distinguishes Northrop Nortronics.

This approach led to a design philosophy which considers the total effectiveness of a system in terms of performance,



reliability specialists, 40 quality control specialists, 124 support equipment 41 maintenance and support specialists, 226 navigation systems specialists, analysis specialists, add 20 years of systems experience, and what have you got?

maintainability, and cost of operation throughout its life.

The Northrop approach developed planning techniques which make it routine for complex avionic systems to perform 100% at first flight... as well as quality control techniques which assure reliability from that point on.

It built up an organizational and production efficiency which has compiled an enviable record of meeting delivery commitments within the limits of both time and cost.

And it has led, time and again, to breakthroughs which have significantly advanced the state of the art.

Specialists and managers, our team has been working together for 20 years. **NORTHROP NORTRONICS**

LETTERS

Sirs:

At our firm we have been engaged for the past three years in research on optical character-recognition systems. The analysis of a graphic symbol to be recognized by a machine is carried out by a set of integrators that detect in each small region of the visual field the orientations of the contrast boundaries constituting the outline of the symbol; thus the set of measurements consists of a set of vector quantities.

You can imagine, then, the mounting excitement with which we read David H. Hubel's article "The Visual Cortex of the Brain" [SCIENTIFIC AMERICAN, November, 1963], to discover that this is indeed one of the basic mechanisms of mammalian visual perception. If instead of the intensity of impulse flux you substitute the amplitude of the signal at one of our integrator outputs, the diagram on page 60 of Hubel's article could well be the illustration for our vector principle.

About the only difference (*vive la différence!*) between the biological and the electronic realizations is that for reasons of economy our machine detects only eight orientations (direction quantized to steps of 45 degrees), and one set of integrators processes sequentially the entire visual field through a single

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scanner, whereas nature applies a large enough number of her exquisite ultraminiature logical elements to do the whole thing simultaneously and in a much larger number of orientations. Nevertheless, with electronic speeds, we hope to read 1,000 characters a second.

MORTON NADLER

Compagnie des Machines Bull
Paris

Sirs:

I enjoyed reading Roger Revelle's article "Water" in your excellent issue "Technology and Economic Development" [September, 1963]. However, the article contains an inaccuracy if it implies that nighttime dew is derived from the atmosphere and can be a significant contribution toward meeting the water needs of crops in arid lands. This widely and persistently held misconception probably arises from two observations. First, so-called "dew gauges"—usually thin plates mounted close to the surface—often collect significant amounts of water. Second, vegetation in arid zones, as elsewhere, is often soaking wet with dew early in the morning.

Careful studies of the dew phenomenon, directly with weighing devices and indirectly by micrometeorological methods, have demonstrated that dewfall—that is, a gain of moisture from the atmosphere by the surface—is rare and usually is insignificant.

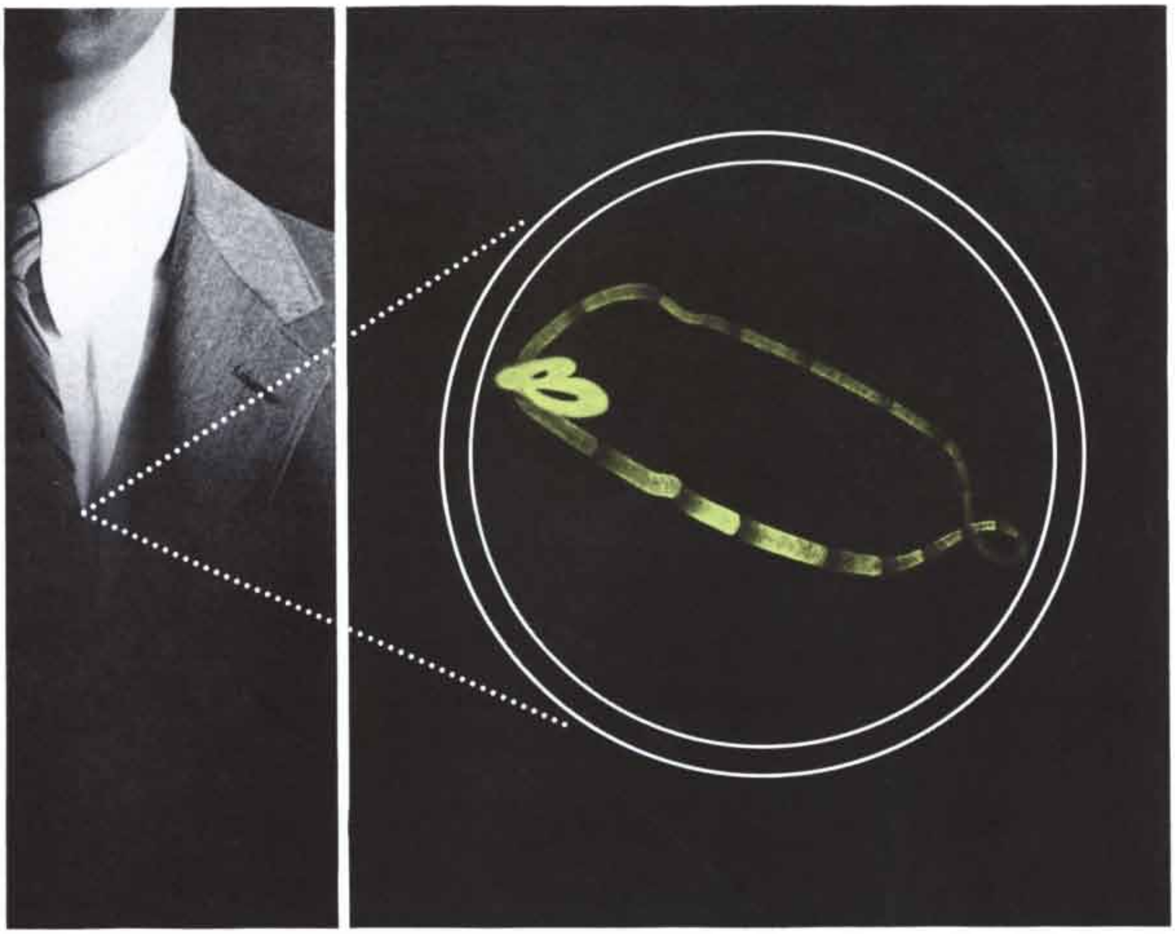
It is true that we may find large amounts of dew on vegetation in an arid climate such as that of Arizona and central California. This water, however, evaporates from the soil and is recondensed on the colder surfaces of the plants. Direct measurement of the water balance sometimes shows a continued net loss during the night while the dew formation goes on. "Dew gauges" show a net gain under such conditions.

A theoretical analysis of the problem also shows that dewfall, that is, accretion of moisture, can be very small only and is unlikely to occur at all in an arid environment. . . .

The ancient Greek philosophers held that dew was the sweat of the earth, arising from its pores. Modern science confirms this view and refutes the belief that dew comes from the atmosphere.

C. H. M. VAN BAVEL

U.S. Water Conservation Laboratory
U.S. Department of Agriculture
Tempe, Ariz.



One of a series briefly describing GM's research in depth

HOW A CAR RESPONDS TO CROSSWINDS

A rocket engine is being used by an engineering research group at our Laboratories to study the effects of crosswinds on the directional behavior of passenger cars.

Mounted on the side of a full-size car, the lightweight engine can exert a maximum thrust of 200 pounds . . . a force equivalent to a 25-mph crosswind hitting a vehicle traveling 60 mph. Because a vehicle's aerodynamic center of pressure is a function of body shape, engineers—simply by shifting rocket engine location—have been able to evaluate the effects of body changes on a car's response to crosswind disturbances.

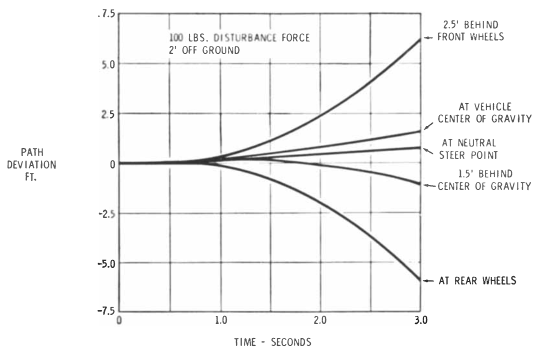
This flexibility of location is one of several advantages of the new system over previous attempts to study crosswind effects. Both force and time of the thrust is accurately controlled for each test run.

An important result of this work has been the experimental verification of theoretical equations of lateral motion. These equations form a mathematical model of the vehicle that we are now using in computer simulation of car handling.

This directed interplay of theory, experiment and analysis is another example of how GM engineers are working to find a better way—through research in depth.

General Motors Research Laboratories

Warren, Michigan



Path deviation of a vehicle traveling 60 mph for various centers of pressure.

IBM computers, science and you:

Your systems design problem just shrunk

Computer simulation is a great idea—especially in systems design. It can help you pre-test and improve performance of a steel mill layout, a communications network, a job shop.

But programming the computer for a simulation can be a problem. It takes time . . . and a thorough knowledge of programming. It can be expensive.

So we've developed a program to make systems simulation easier.

Any experienced systems engineer can use the IBM General Purpose Systems Simulator II. You describe the job with block diagrams and FORTRAN-like statements.

Once you describe the system in this simple engineering language, an IBM 7090 computer takes over and functions like the real-life system would. You can compress days, weeks, even months of real-life operation into a few minutes of 7090 running time.

You can change parameters or operating rules at will. You can see how system components interact. You can improve performance while your system is still only a computer program.

The General Purpose Systems Simulator II works on systems that involve transactions, traffic, people and equipment that compete for services of other people or equipment and form queues at key points in the system while waiting for service.

The program can handle up to 800 blocks, 200 facilities, 200 queues, 100 functions, 100 tables, 50 variables and 1000 transactions.

If your system is bigger than this, you have a real giant of a problem. But we still may be able to help you cut it down to manageable size. Try us. Write.

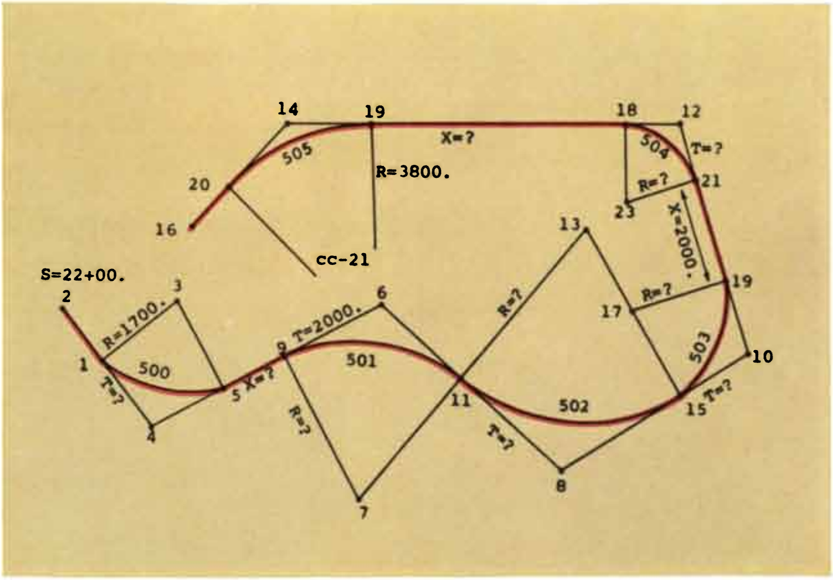
Semi-automatic geometry

Here's another new IBM computer program—this one useful to anyone who designs bridges, builds roads, plans housing developments.

We call it COGO I. COGO I lets an engineer program an IBM 1620 computer using the same notation he'd use in solving his problem by hand. The "language" is made up of 43 terms like LINE/INTERSECT, ARC/INTERSECT, ALIGNMENT, etc.

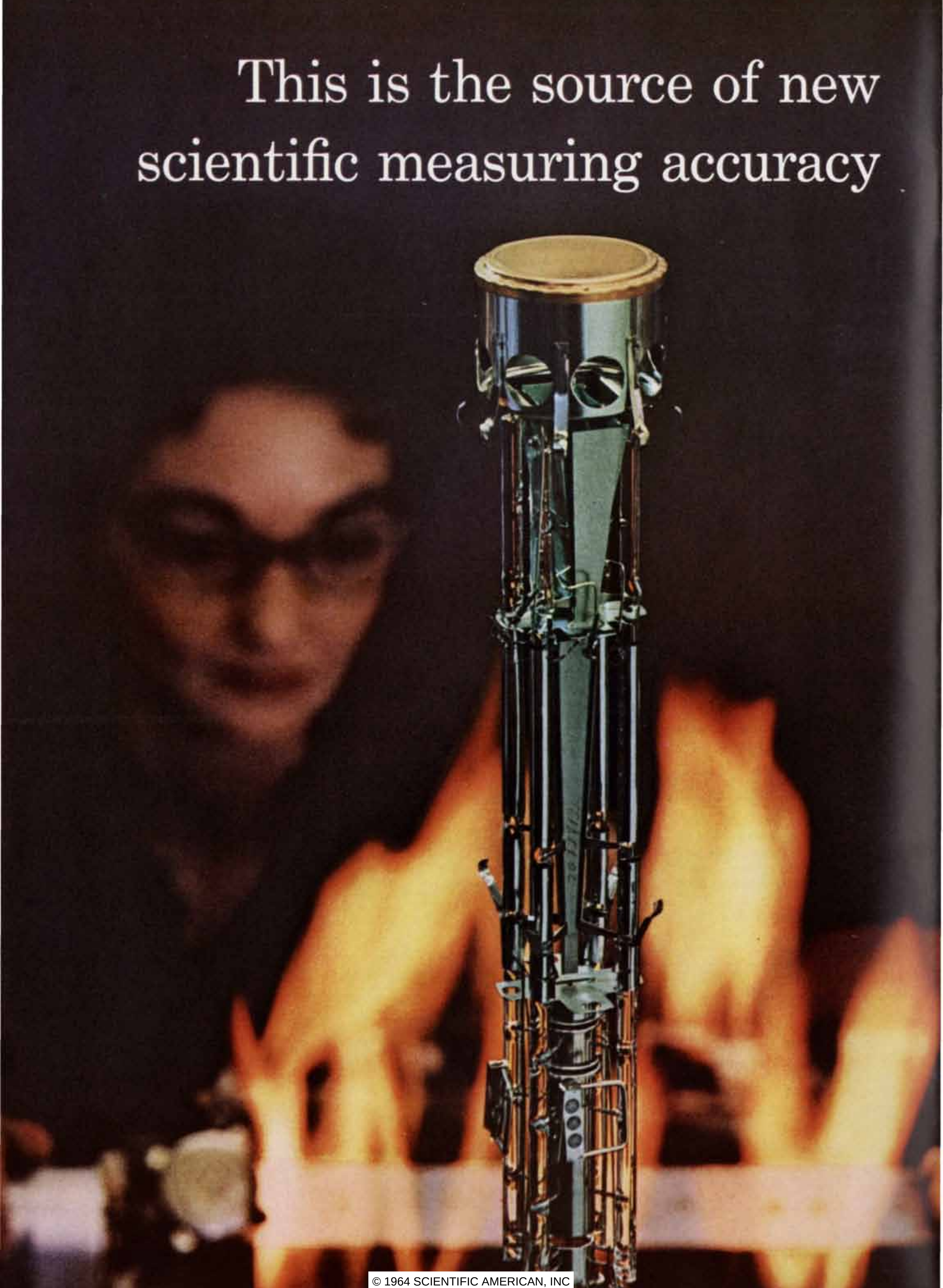
With COGO I, you can easily and quickly solve problems in triangulation, curve geometry, traverse adjustment, highway alignment and structural geometry—without previous computer training. You can add your own problem statements to the language.

The program works with punched card input or random access storage in an IBM 1311 Disk File. You can run the program for as little as $12 an hour. Ask your IBM representative about it.



For more information, write for literature to International Business Machines Corporation, Data Processing Division, 112 East Post Road, White Plains, New York. Department 805-S3.

IBM
DATA PROCESSING


This is the source of new
scientific measuring accuracy

PROGRESS

in scientific measurement depends in part on continuing improvement of the oscilloscope, a basic measuring tool that visually displays repetitive or fleeting electrical phenomena.

Dramatic improvements in circuitry have made the oscilloscope a versatile and indispensable tool. Yet, refined and sophisticated as scope circuitry may be, the limitations of conventional cathode ray tubes can create reading errors which only improved CRT design can correct. Hewlett-Packard has combined both electronic and *manufacturing* achievements to produce oscilloscope CRTs that come closer than ever before to eliminating human reading error.

Three basic improvements have been made: a 50% greater picture size on a high-frequency scope, removal of parallax viewing error, and the elimination of reflected glare.

For high speed (50 MC) oscillography, hp has produced an entirely new cathode ray display tube. This new 12,000 volt CRT displays high speed electrical signals on a full 6 cm x 10 cm calibrated screen (50% larger than previously available for high frequencies). Deflection defocusing has been eliminated, and the sensitivity of the CRT has been doubled. Less amplification is needed to swing the electron beam so simpler, more reliable driving circuits can be used. The 50% larger display that stays in focus at full deflection significantly reduces the reading error.

Second, hp developed a manufacturing technique to eliminate a parallax viewing error which, on most oscilloscopes sold today, can be as great as 5% unless every portion of the trace is viewed from precisely in front of that part of the screen. This parallax error was caused by a separation as great as ¼″ between the trace, falling on the inside of the CRT face, and the square-centimeter-scribed scaling graticule, placed on the outside surface of the CRT face. hp completely eliminated parallax error by placing the graticule on the inside of the tube, in the same plane as the trace. Readout is now identical from any angle.

Finally, glare and reflections from ambient light have always plagued scope users. Viewing screens blocked out reflected light but limited viewing to one person at a time. Now, an etching process on the surface of the safety glass face plate on hp CRTs eliminates glare, at the same time preserving clear viewing.

Illustrated here is the electron gun against a background of flame from the gas jets of the assembly fixture.

Hewlett-Packard oscilloscope technology includes the continuing improvement of cathode ray tube design and construction for new scientific measuring accuracy.

hp 175A 50 MC Universal Oscilloscope

is the first hp scope to incorporate the new 12 kv no-parallax crt as standard equipment, although the no-parallax feature is now available as standard equipment on other hp scopes. The 175A offers single channel viewing to 50 mc, and four channel viewing to 40 mc, high sensitivity, sweep delay, time marker, X-Y recorder output; simple calibration and maintenance; preset automatic trigger over entire bandwidth; hp modular packaging for bench and rack mount in a single instrument. $1,325 (Basic instrument. Versatile plug-ins optional at extra cost.)

An extra measure of quality

HEWLETT PACKARD COMPANY

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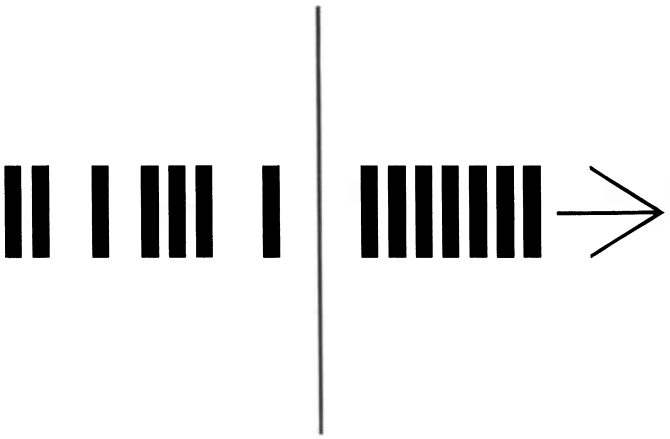


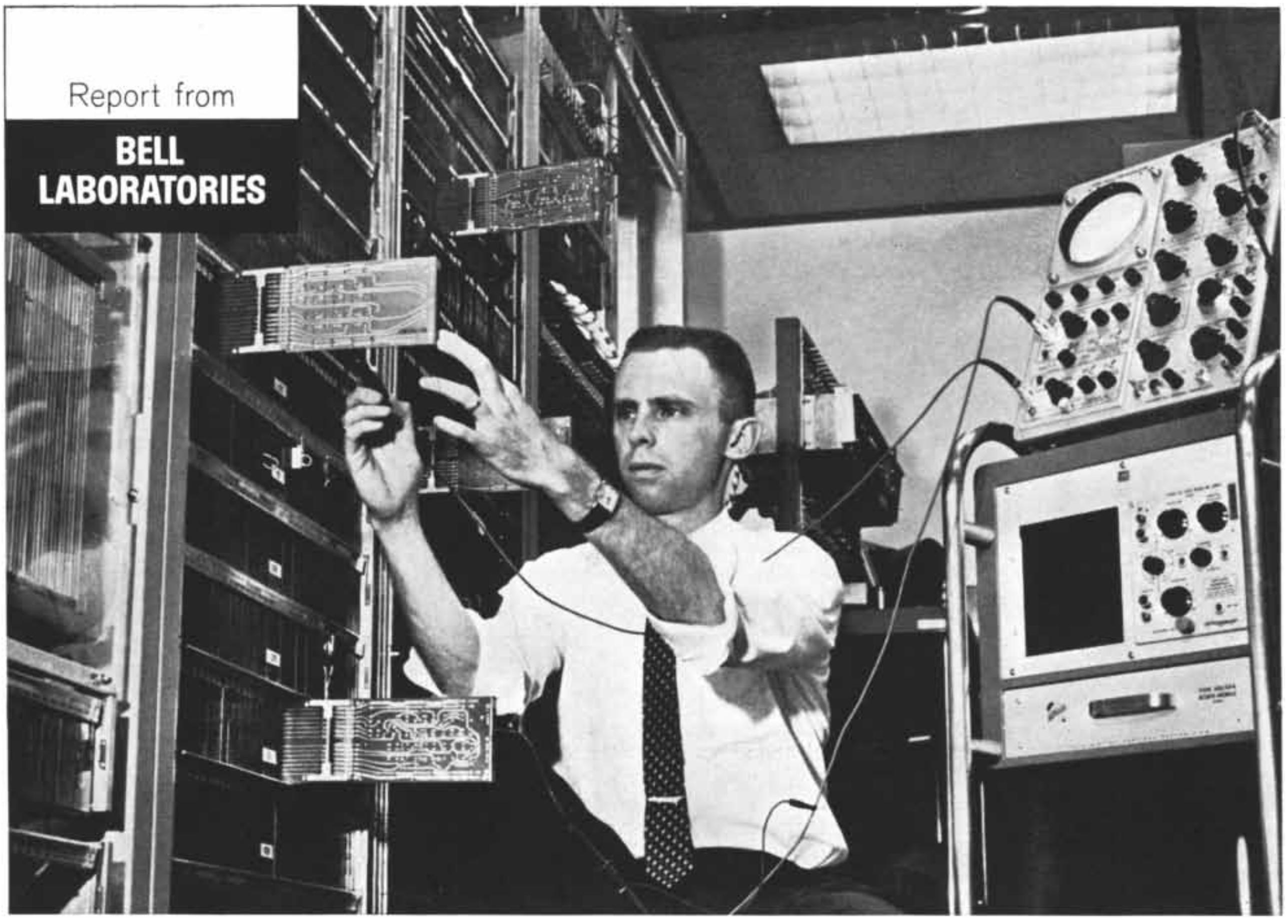
50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

FEBRUARY, 1914: "The notion of a universal medium permeating all space has undergone many vicissitudes. The sphere of celestial fire of the Alexandrians and the interstellar whirlpools of Descartes gave way to the solid theory which was elaborated with immense skill by Young, Fresnel, Stokes and Kelvin only to give way to the electromagnetic ether of Maxwell. At the present time there are at least three theories: one considers the ether as an incompressible medium, very rigid and very dense; another considers it composed of particles much smaller than electrons, and the third denies its existence altogether and seeks to eradicate it from the list of physical theories. It is this last theory which gains more and more adherents day by day. We are in a revolutionary epoch, where the tendency is toward explaining phenomena in terms of emission rather than undulation and of particles rather than fluids. And once more we see reappearing the mysterious and rather terrifying notion of the absolute 'nothingness' of outer space which one imagined to be successfully abolished by the introduction of the ether."

"Mr. Rodman Wanamaker of Philadelphia has decided to build a machine which will compete for the prize of $50,000 offered by Lord Northcliffe for the first crossing of the Atlantic Ocean in an aeroplane. The building of the machine will be intrusted to Mr. Glenn H. Curtiss, who has decided that the prize can be won in a flight of a single stage lasting not more than 15 hours. The machine will be equipped with a motor of 200 horse-power, which Mr. Curtiss is now testing."

"The Russian engineer Sikorsky has completed a machine nearly twice the size of his previous one. The dimensions of this great biplane are stupendous. In span it measures 121 feet; the chord of the planes is nine feet; the total lifting area, no less than 1,950 square feet. From nose to tail the fuselage measures 65 feet. Driven by four motors develop-



Bell Laboratories' E. G. Hughes tests printed circuit boards in experimental central office control equipment for 101-Electronic Switching System. The system automatically detects trouble, switching out a defective unit and switching in a duplicate unit so service is not interrupted.

High-Speed Switching System Provides New Telephone Services for Business

A new electronic switching system designed to meet the special needs of business customers has been developed at Bell Telephone Laboratories. This system provides many new telephone services such as a way for reaching a seven- or ten-digit number by dialing only three digits, setting up conference calls by dialing other customers into the conversation, and automatically transferring incoming calls from your phone to another by predialing special codes.

A notable feature of the new system is a high-speed control unit. Operating from a telephone switching center, the unit scans—thousands of times per second—all the telephone connections in dozens of business offices that may be located many miles apart. It spends only two-thousandths of a second in each office, but in that time it determines what has to be done and arranges for the necessary actions.

Another feature of the new system is the high-capacity memory. From this, the control unit can draw, in eight-millionths of a second, such specific instructions as how to handle a certain call.

The new switching system operates compatibly with existing electromechanical switching systems in the Bell System. Such Bell Laboratories inventions as the transistor are indispensable to its compactness and the high reliability of its operation. The system was developed for use by businesses as a private branch exchange, and a model has been installed by Western Electric for trial by two New Brunswick, New Jersey, companies.

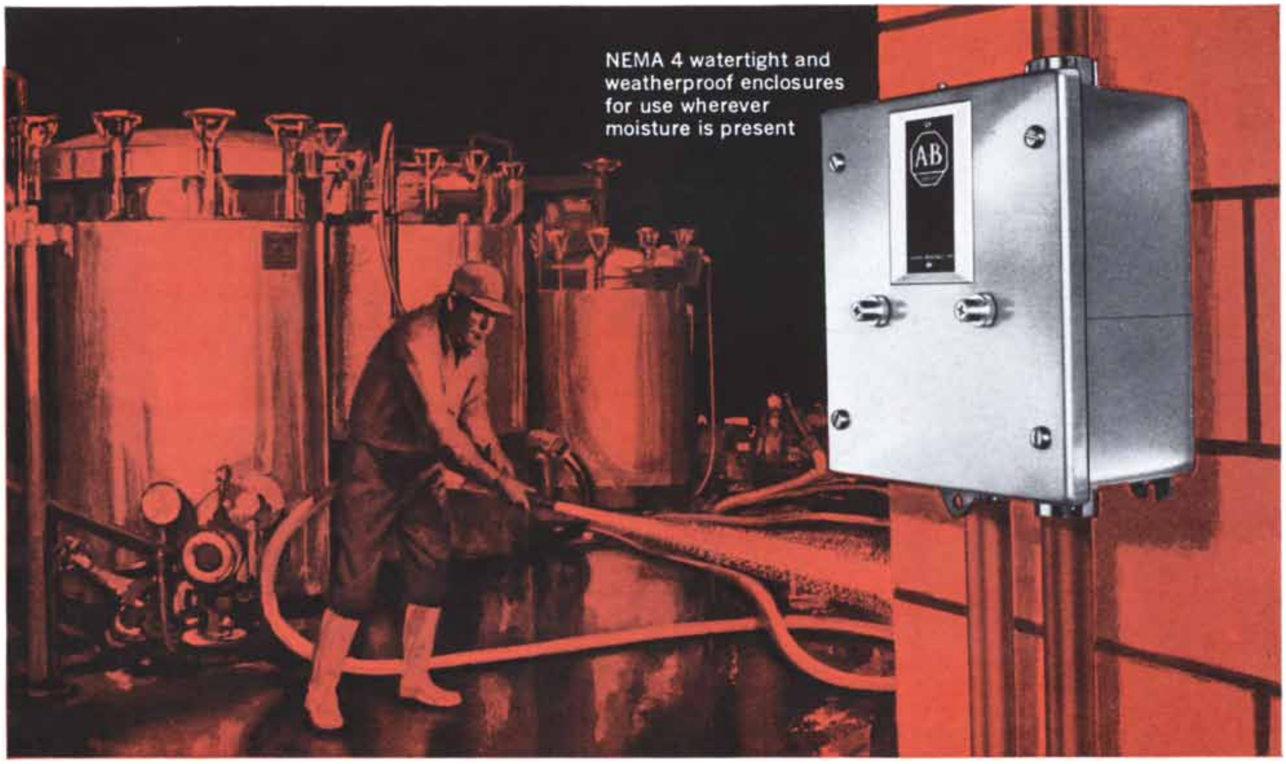
BELL TELEPHONE LABORATORIES
World center of communications research and development

ing a total of 400 horse-power, the machine itself weighs about 7,500 pounds, or close upon four tons. On its first flight it carried 10 passengers. Sikorsky seems to have succeeded in evolving what may justly be regarded as the forerunner of the great weight-carrying aeroplanes of the future."

Scientific American.

FEBRUARY, 1864: "The rebels have built a new submarine vessel at Mobile with the intention of sinking any of our ships that may be lying there. The battery contains nothing new in its construction or principle but is the same thing that has been used here several times for more peaceful purposes. Many years ago a submarine vessel, similar in all respects to the rebel affair except in shape, was built at one of the iron-works on the East river in New York. The rebel battery sinks by letting water into certain compartments and rises again by pumping it out; she has a horizontal projecting flange at the bow, which can be turned up or down so as to deflect the course of the vessel to the surface or the bottom of the channel, and she also has pumps for compressing air, so that the crew can remain below the surface for some time. The battery is also to carry torpedoes united by a chain, which are to be carried under the ship to be destroyed and there set free, when it is supposed they will be light enough to rise to the surface and hug the ship to be blown up. The rebel vessel also has a screw, which is driven by an engine as usual. This ship may accomplish the destruction of some of our vessels and is in any case a disagreeable customer which should be got rid of as soon as possible."

"Professor Agassiz lately delivered a course of three lectures before the Smithsonian Institution, and the greater part of the last one was devoted to a description of the phenomena which indicate that the continent of North America had at one time been overlaid by dense and unbroken masses of ice, moving from the North to the South. After stating the grounds on which the 'earthquake theory' was inadequate to explain the peculiar drift deposited on the surface of the continent from the Arctic to the 36th or 40th parallel of latitude, Prof. Agassiz estimated that the ice which deposited this drift and produced its other attendant phenomena must have been five or six thousand feet thick. But whence came



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the cold which produced such a thickness of ice? This query was answered by supposing that there had been injected into the sea from the subterranean fires of the earth below it a vast mass of melted material, thus generating an immense volume of vapor, which, escaping for ages into the upper air, was condensed and fell in the shape of snow and hail. By this mass of snow and hail the temperature of the earth's climate was reduced from the comparative warmth which preceded it, even in Arctic regions, and the world entered on the 'cold period,' which it was the object of the lecturer to describe and to account for while describing."

"The nearest fixed stars are so remote that light, moving at the rate of 192,000 miles in a second, occupies three years in coming from them to us, and yet it seems probable that we are to learn what some of the substances are which enter into the composition of these distant and unapproachable bodies. At the last meeting of the Royal Society of Great Britain the president made the following remarks in relation to this inquiry:—'The researches of Kirchhoff and Bunsen have rendered it in a high degree probable that we shall be able to obtain much insight into the chemical nature of the atmospheres of the brighter fixed stars by observing the dark lines in their spectra and comparing them with the bright lines in the spectra of elementary and perhaps also of compound bodies in the state of incandescent gas or vapor. In a short paper read to the society on the 26th of last February and published in the *Proceedings*, Mr. Huggins and Dr. Miller have described and figured the spectra of three of the brighter stars, and this part of the inquiry will doubtless be continued. In a paper since presented to the society Mr. Huggins describes the means employed for practically determining with accuracy the positions of any stellar lines which may be observed with reference to known points of the spectrum and has given beautiful maps of the spectra of 24 of the elementary bodies under the action of the inductive discharge, reserving others for a future communication. When the inquiry is completed, it is possible that we may obtain an amount of knowledge respecting the constitution of those distant heavenly bodies of which we have at present little conception.'"

"More shells were discharged in the single battle of Gettysburg than were employed in all the battles that Napoleon ever fought."


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THE AUTHORS

LEONARD BERKOWITZ ("The Effects of Observing Violence") is professor of psychology at the University of Wisconsin. A graduate of New York University, Berkowitz received a Ph.D. in psychology from the University of Michigan in 1951. From 1951 to 1955 he did research on bomber-crew effectiveness for the U.S. Air Force at the Human Resources Research Center in San Antonio, Texas. A member of the Wisconsin faculty since 1955, Berkowitz will spend the academic year 1964–1965 doing research at the University of Oxford in England. He is the author of *Aggression: A Social Psychological Analysis*, published by McGraw-Hill in 1962.

JOHN E. AMOORE, JAMES W. JOHNSTON, JR., and MARTIN RUBIN ("The Stereochemical Theory of Odor") collaborated in the writing of this article by means of an extensive cross-country correspondence. Amoore does his share of the research at the Western Regional Research Laboratory of the U.S. Department of Agriculture in Albany, Calif. A native of England, he has an M.A. and a D.Phil. in biochemistry from the University of Oxford. Since 1952 he has done research in the chemistry department of the California Institute of Technology, in the botany department of the University of Edinburgh and in the zoology department of the University of California at Berkeley. Amoore worked out the theoretical basis of the stereochemical theory of odor in 1952 while still an undergraduate at Oxford. He began his long correspondence and collaboration with Johnston and Rubin in 1954 but did not meet them until 1962. Both Johnston and Rubin are members of the faculty of Georgetown University. Johnston is associate professor of physiology in the School of Medicine. A graduate of Syracuse University, he obtained a Ph.D. in physiology and ecology from Harvard University in 1936. Since joining the Georgetown faculty in 1950 he has worked mainly on the problem of measuring olfaction in humans, rabbits, dogs and insects. Rubin is associate professor of chemistry both in the Georgetown School of Medicine and the Georgetown Graduate School. He received a B.S. from the City College of the City of New York in 1936 and a Ph.D. in organic chemistry from Columbia University in 1942. His original synthesis of the pimelates and lactones was a major contribution to this joint research effort.

JOHN A. O'KEEFE ("Tektites and Impact Fragments from the Moon") is assistant chief of the theoretical division at the National Aeronautics and Space Administration's Goddard Space Flight Center in Greenbelt, Md. O'Keefe received an A.B. from Harvard College in 1937 and a Ph.D. in astronomy from the University of Chicago in 1941. He spent a year as professor of mathematics and astronomy at Brenau College in Gainesville, Ga., before joining the U.S. Army Corps of Engineers as a mathematician in 1942. His first project for the Corps involved the establishment of military co-ordinate systems for artillery survey and fire. Later he worked on the geodetic mapping of China and on the problem of providing accurate geodetic data for guided missiles. He also helped to develop the technique of using "occultations" of stars and planets rather than solar eclipses to measure accurately the distance from the earth to the moon. Since joining the Goddard Space Flight Center in 1958 O'Keefe has worked mainly on the tektite problem.

ROBERT S. SPEIRS ("How Cells Attack Antigens") is associate professor of anatomy at the Downstate Medical Center of the State University of New York College of Medicine. A native of Arkansas, Speirs was graduated from the University of Wisconsin in 1941. During World War II he served in an "antigen-printing" unit of the U.S. Army in Europe. Following the war he returned to the University of Wisconsin on a U.S. Public Health Service Fellowship; he acquired a Ph.D. in zoology there in 1950. From 1949 to 1955 Speirs did research at the Roscoe B. Jackson Memorial Laboratory in Bar Harbor, Me. He joined the Downstate faculty in 1956. Since 1956 he has also been visiting investigator at the Brookhaven National Laboratory.

GEOFFREY F. CHEW, MURRAY GELL-MANN and ARTHUR H. ROSENFELD ("Strongly Interacting Particles") are nuclear physicists at institutions in California. Chew is professor of physics at the University of California at Berkeley. A graduate of George Washington University, where his interest in physics was sparked by the lectures of George Gamow, Chew worked on early studies of the hydrogen bomb as an assistant to Edward Teller and Enrico Fermi at the Los Alamos Scientific Laboratories. He continued his studies under

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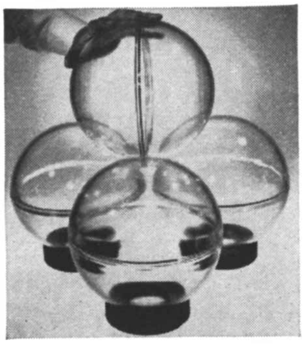

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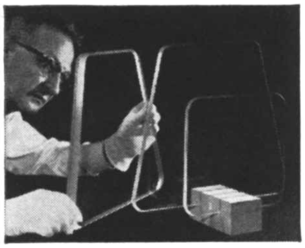

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Fermi at the University of Chicago, acquiring a Ph.D. there in 1948. He first went to Berkeley in 1949 but resigned from the faculty in 1950 as a result of the loyalty oath controversy. After five years at the University of Illinois and one year as a member of the Institute for Advanced Study in Princeton, N.J., he returned to Berkeley in 1957 as professor of physics. He was awarded the Hughes Prize of the American Physical Society in 1962. Gell-Mann is professor of physics at the California Institute of Technology. A graduate of Yale University, he received a Ph.D. in physics from the Massachusetts Institute of Technology in 1951. He spent a year at the Institute for Advanced Study before joining the Institute for Nuclear Studies of the University of Chicago, where he also worked with Fermi. He went to Cal Tech in 1955; in 1959 he won the Dannie Heineman Prize of the American Institute of Physics. Gell-Mann was the coauthor, with E. P. Rosenbaum, of "Elementary Particles," which appeared in the July 1957 issue of SCIENTIFIC AMERICAN. Rosenfeld is professor of physics at the University of California at Berkeley. He was graduated from the Virginia Polytechnic Institute in 1944 and obtained a Ph.D. in physics, also under Fermi, from the University of Chicago in 1954. He did research for a year at the Institute for Nuclear Studies at Chicago before going to Berkeley in 1956. As a member of the group of experimental physicists under Luis W. Alvarez at Berkeley's Lawrence Radiation Laboratory, Rosenfeld has helped to develop high-speed computer programs for analyzing the nuclear events in bubble-chamber photographs.

CARL R. EKLUND ("The Antarctic Skua") was chief of the Polar and Arctic Branch of the U.S. Army Research Office; he died after completing the article in this issue. Eklund was born in Tomahawk, Wis., in 1909 and obtained a B.A. from Carleton College in 1932. After working for three years as a forestry foreman he obtained an M.S. from Oregon State College in 1936. He made his first trip to Antarctica in 1939 as an ornithologist with the Byrd expedition. On this occasion he made one of the most extraordinary Antarctic treks on record, traveling 1,264 miles by dog sledge in 84 days and mapping more than 350 miles of the Antarctic coast. He also discovered a group of islands in King George VI Sound, which has since been named the Eklund Islands. During World War II he served as a major in the Arctic section of the Arctic Desert

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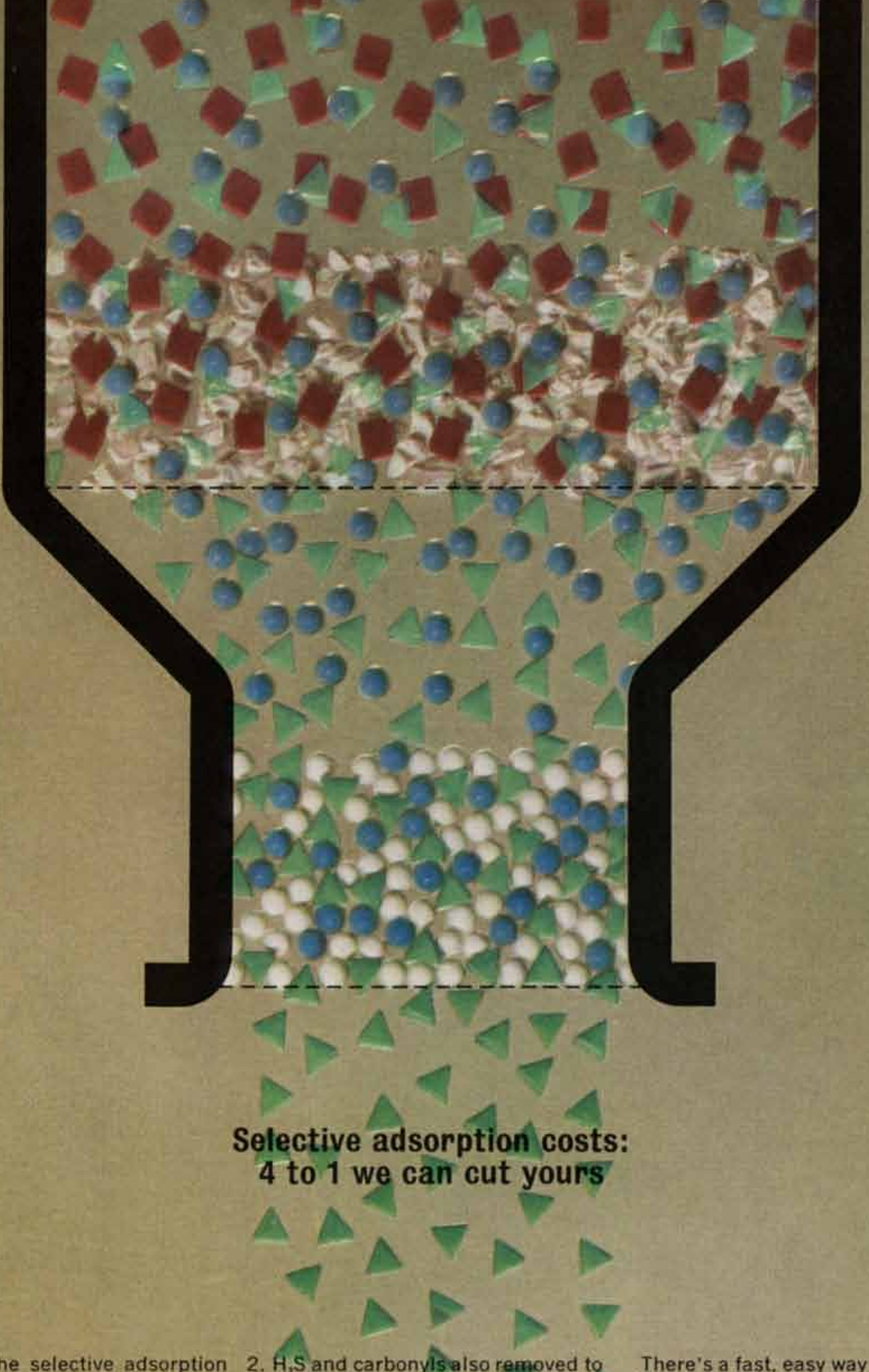
Tropic Information Center of the Army Air Force. He worked as a research biologist and ornithologist for the Fish and Wildlife Service until 1957, when he became scientific leader at Wilkes Station in Antarctica for the duration of the International Geophysical Year. In 1959 Eklund received a Ph.D. in zoology from the University of Maryland; his doctoral thesis on the south polar skua formed the basis of the present article.

WILLIAM H. PIERCE ("Redundancy in Computers") is assistant professor of electrical engineering at the Carnegie Institute of Technology. He is also senior engineer at the Westinghouse Research Laboratory in Pittsburgh. Pierce obtained an A.B. in physics from Harvard College in 1955. After three years in the Navy he acquired an M.S. and a Ph.D. in electrical engineering from Stanford University in 1959 and 1961 respectively. He has been at the Carnegie Institute since 1961. Among his current research interests are the function of error-correction in the human brain and the role of redundancy in human memory.

WILLIAM L. LANGER ("The Black Death") is Archibald Cary Coolidge Professor of History at Harvard University. Langer was born in Boston in 1896 and took his degrees at Harvard. He also studied at the University of Vienna in 1921 and 1922. He has been a member of the history department at Harvard since 1926. A veteran of the Saint-Mihiel and Argonne engagements of World War I, Langer served as chief of the Research and Analysis Branch of the Office of Strategic Services during World War II. In 1946 he reorganized the foreign intelligence services of the State Department as Special Assistant to the Secretary of State. From 1950 to 1952 he served as assistant director of the Central Intelligence Agency. He is at present a member of the President's Foreign Intelligence Advisory Board. Langer was director of the Russian Research Center and the Center for Middle Eastern Studies at Harvard from 1954 to 1959. In 1957 he was elected president of the American Historical Association. He spent the academic year 1959–1960 at the Center for Advanced Study in the Behavioral Sciences in Palo Alto, Calif. Langer has written extensively in the fields of European and American diplomatic history; he is also the editor of *An Encyclopedia of World History*, published in 1940, and of the series "The Rise of Modern Europe," of which 13 volumes have appeared to date.



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The Effects of Observing Violence

Experiments suggest that aggression depicted in television and motion picture dramas, or observed in actuality, can arouse certain members of the audience to violent action

by Leonard Berkowitz

An ancient view of drama is that the action on the stage provides the spectators with an opportunity to release their own strong emotions harmlessly through identification with the people and events depicted in the play. This idea dates back at least as far as Aristotle, who wrote in *The Art of Poetry* that drama is "a representation . . . in the form of actions directly presented, not narrated; with incidents arousing pity and fear in such a way as to accomplish a purgation of such emotions."

Aristotle's concept of catharsis, a term derived from the Greek word for purgation, has survived in modern times. It can be heard on one side of the running debate over whether or not scenes of violence in motion pictures and television programs can instigate violent deeds, sooner or later, by people who observe such scenes. Eminent authorities contend that filmed violence, far from leading to real violence, can actually have beneficial results in that the viewer may purge himself of hostile impulses by watching other people behave aggressively, even if these people are merely actors appearing on a screen. On the other hand, authorities of equal stature contend that, as one psychiatrist told a Senate subcommittee, filmed violence is a "preparatory school for delinquency." In this view emotionally immature individuals can be seriously affected by fighting or brutality in films, and disturbed young people in particular can be led into the habit of expressing their aggressive energies by socially destructive actions.

Until recently neither of these arguments had the support of data obtained by controlled experimentation; they had to be regarded, therefore, as hypotheses, supported at best by unsystematic observation. Lately, however, several psychologists have undertaken laboratory tests of the effects of filmed aggression. The greater control obtained in these tests, some of which were done in my laboratory at the University of Wisconsin with the support of the National Science Foundation, provides a basis for some statements that have a fair probability of standing up under continued testing.

First, it is possible to suggest that the observation of aggression is more likely to induce hostile behavior than to drain off aggressive inclinations; that, in fact, motion picture or television violence can stimulate aggressive actions by normal people as well as by those who are emotionally disturbed. I would add an important qualification: such actions by normal people will occur only under appropriate conditions. The experiments point to some of the conditions that might result in aggressive actions by people in an audience who had observed filmed violence.

Second, these findings have obvious social significance. Third, the laboratory tests provide some important information about aggressive behavior in general. I shall discuss these three statements in turn.

Catharsis appeared to have occurred in one of the first experiments, conducted by Seymour Feshbach of the University of Colorado. Feshbach deliberately angered a group of college men; then he showed part of the group a filmed prizefight and the other students a more neutral film. He found that the students who saw the prizefight exhibited less hostility than the other students on two tests of aggressiveness administered after the film showings. The findings may indicate that the students who had watched the prizefight had vented their anger vicariously.

That, of course, is not the only possible explanation of the results. The men who saw the filmed violence could have become uneasy about their own aggressive tendencies. Watching someone being hurt may have made them think that aggressive behavior was wrong; as a result they may have inhibited their hostile responses. Clearly there was scope for further experimentation, particularly studies varying the attitude of the subjects toward the filmed aggression.

Suppose the audience were put in a frame of mind to regard the film violence as justified—for instance because a villain got a beating he deserved. The concept of symbolic catharsis would predict in such a case that an angered person might enter vicariously into the scene and work off his anger by thinking of himself as the winning fighter, who was inflicting injury on the man who had provoked him. Instead of accepting

TYPICAL EXPERIMENT tests reaction of angered man to filmed violence. Experiment begins with introduction of subject (*white shirt*) to a man he believes is a co-worker but who actually is a confederate of the author's. In keeping with pretense that experiment is to test physiological reactions, student conducting the experiment takes blood-pressure readings. He assigns the men a task and leaves; during the task the confederate insults the subject. Experimenter returns and shows filmed prizefight. Confederate leaves; experimenter tells subject to judge a floor plan drawn by confederate and to record opinion by giving confederate electric shocks. Shocks actually go to recording apparatus. The fight film appeared to stimulate the aggressiveness of angered men.

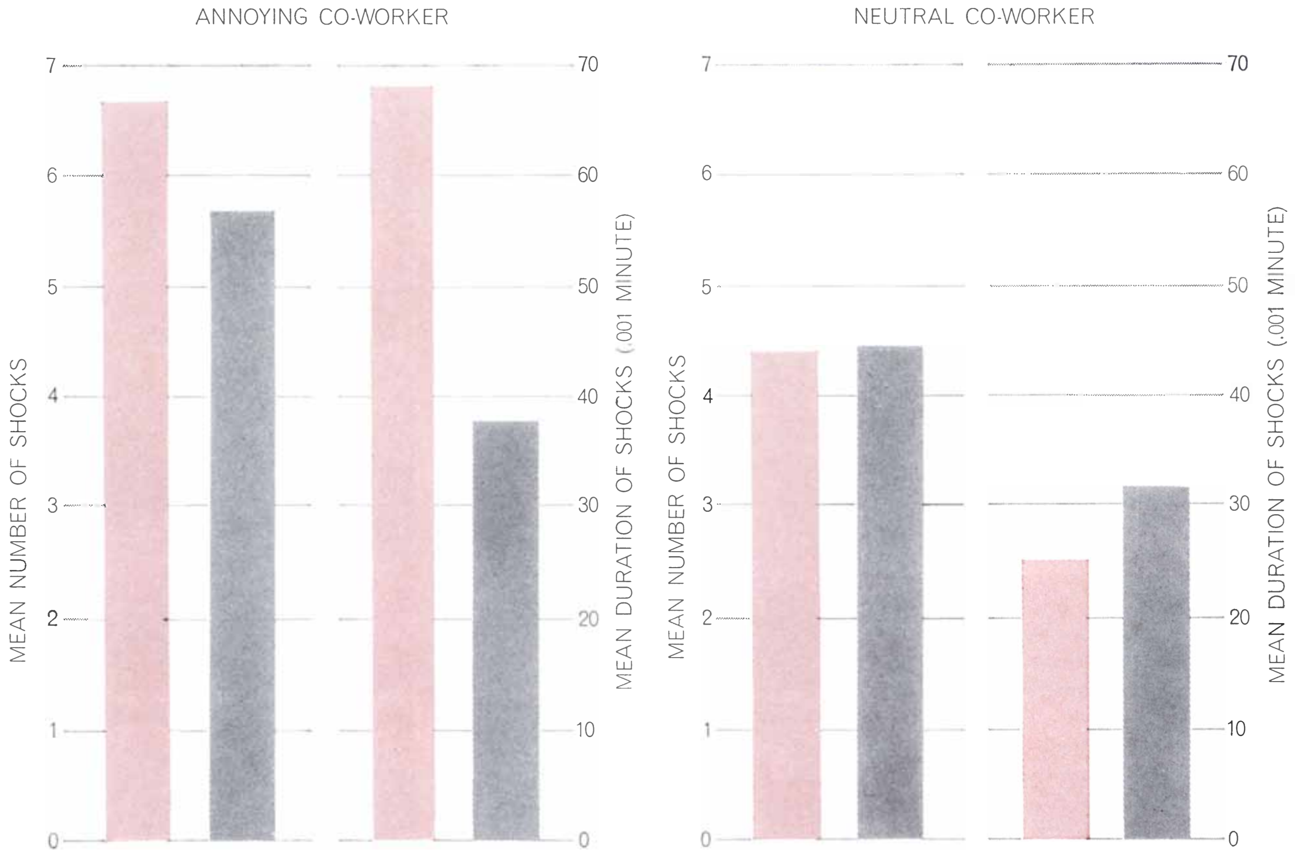
this thesis, my associates and I predicted that justified film aggression would lead to stronger rather than weaker manifestations of hostility. We believed that the rather low volume of open hostility in the Feshbach experiment was attributable to film-induced inhibitions. If this were so, an angered person who saw what appeared to be warranted aggression might well think he was justified in expressing his own hostile desires.

To test this hypothesis we conducted three experiments. Since they resulted in essentially similar findings and employed comparable procedures, I shall describe only the latest. In this experiment we brought together two male college students at a time. One of them was the subject; the other was a confederate of the experimenter and had been coached on how to act, although of course none of this was known to the subject. Sometimes we introduced the confederate to the subject as a college boxer and at other times we identified him as a speech major. After the introduction the experimenter announced that the purpose of the experiment was to study physiological reactions to various tasks. In keeping with that motif he took blood-pressure readings from each man. Then he set the pair to work on the first task: a simple intelligence test.

During this task the confederate either deliberately insulted the subject—for example, by remarks to the effect that "You're certainly taking a long time with that" and references to "cow-college students" at Wisconsin—or, in the conditions where we were not trying to anger the subject, behaved in a neutral manner toward him. On the completion of the task the experimenter took more blood-pressure readings (again only to keep up the pretense that the experiment had a physiological purpose) and then informed the men that their next assignment was to watch a brief motion picture scene. He added that he would give them a synopsis of the plot so that they would have a better understanding of the scene. Actually he was equipped with two different synopses.

To half of the subjects he portrayed the protagonist of the film, who was to receive a serious beating, as an unprincipled scoundrel. Our idea was that the subjects told this story would regard the beating as retribution for the protagonist's misdeeds; some tests we administered in connection with the experiment showed that the subjects indeed had little sympathy for the protagonist. We called the situation we had created with this synopsis of the seven-minute fight

FILMED AGGRESSION shown in author's experiments was from the motion picture *Champion* and included these scenes in which Kirk Douglas receives a bad beating. Watchers had been variously prepared; after showing they were tested for aggressive tendencies.



RESPONSES OF SUBJECTS invited to commit aggression after seeing prizefight film varied according to synopsis they heard beforehand. One (*colored bars*) called Douglas' beating deserved; the other (*gray bars*) said it was undeserved. After the film the subjects were told they could give electric shocks to an annoying or neutral co-worker based on his "creativeness" in doing a task. Seeing a man receive what had been described as a well-deserved beating apparently lowered restraints against aggressive behavior.

scene the "justified fantasy aggression."

The other subjects were given a more favorable description of the protagonist. He had behaved badly, they were told, but this was because he had been victimized when he was young; at any rate, he was now about to turn over a new leaf. Our idea was that the men in this group would feel sympathetic toward the protagonist; again tests indicated that they did. We called this situation the "less justified fantasy aggression."

Then we presented the film, which was from the movie *Champion;* the seven-minute section we used showed Kirk Douglas, as the champion, apparently losing his title. Thereafter, in order to measure the effects of the film, we provided the subjects with an opportunity to show aggression in circumstances where that would be a socially acceptable response. We separated each subject and accomplice and told the subject that his co-worker (the confederate) was to devise a "creative" floor plan for a dwelling, which the subject would judge. If the subject thought the floor plan was highly creative, he was to give the co-worker one electric shock by depressing a telegraph key. If he thought the floor plan was poor, he was to administer more than one shock; the worse the floor plan, the greater the number of shocks. Actually each subject received the same floor plan.

The results consistently showed a greater volume of aggression directed against the anger-arousing confederate by the men who had seen the "bad guy" take a beating than by the men who had been led to feel sympathy for the protagonist in the film [*see illustration above*]. It was clear that the people who saw the justified movie violence had not discharged their anger through vicarious participation in the aggression but instead had felt freer to attack their tormentor in the next room. The motion picture scene had apparently influenced their judgment of the propriety of aggression. If it was all right for the movie villain to be injured aggressively, they seemed to think, then perhaps it was all right for them to attack the villain in their own lives—the person who had insulted them.

Another of our experiments similarly demonstrated that observed aggression has little if any effectiveness in reducing aggressive tendencies on the part of an observer. In this experiment some angered men were told by another student how many shocks they should give the person, supposedly in the next room, who had provoked them. Another group of angered men, instead of delivering the shocks themselves, watched the other student do it. Later the members of both groups had an opportunity to deliver the shocks personally. Consistently the men who had watched in the first part of the experiment now displayed stronger aggression than did the people who had been able to administer shocks earlier. Witnessed aggression appeared to have been less satisfying than self-performed aggression.

Our experiments thus cast considerable doubt on the possibility of a cathartic purge of anger through the observation of filmed violence. At the very least, the findings indicated that such a catharsis does not occur as readily as many authorities have thought.

Yet what about the undoubted fact that aggressive motion pictures and violent athletic contests provide relaxation and enjoyment for some people? A person who was tense with anger sometimes comes away from them feeling calmer. It seems to me that what happens here is quite simple: He calms down not because he has discharged his anger vicariously but because he was carried away by the events he witnessed. Not thinking of his troubles, he ceased to stir himself up and his anger dissipated. In addition, the enjoyable motion picture or game could have cast a pleasant glow over his whole outlook, at least temporarily.

The social implications of our experiments have to do primarily with the moral usually taught by films. Supervising agencies in the motion picture and television industries generally insist that films convey the idea that "crime does not pay." If there is any consistent principle used by these agencies to regulate how punishment should be administered to the screen villain, it would seem to be the talion law: an eye for an eye, a tooth for a tooth.

Presumably the audience finds this concept of retaliation emotionally satisfying. Indeed, we based our "justified fantasy aggression" situation on the concept that people seem to approve of hurting a scoundrel who has hurt others. But however satisfying the talion principle may be, screenplays based on it can lead to socially harmful consequences. If the criminal or "bad guy" is punished aggressively, so that others do to him what he has done to them, the violence appears justified. Inherent in the likelihood that the audience will regard it as justified is the danger that some angered person in the audience will attack someone who has frustrated *him*, or perhaps even some innocent person he happens to associate with the source of his anger.

Several experiments have lent support to this hypothesis. O. Ivar Lövaas of the University of Washington found in an experiment with nursery school children that the youngsters who had been exposed to an aggressive cartoon film displayed more aggressive responses with a toy immediately afterward than a control group shown a less aggressive film did. In another study Albert Bandura and his colleagues at Stanford University noted that preschool children who witnessed the actions of an aggressive adult in a motion picture tended later, after they had been subjected to mild frustrations, to imitate the kind of hostile behavior they had seen.

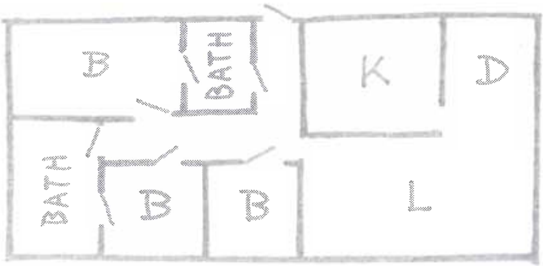
This tendency of filmed violence to stimulate aggression is not limited to children. Richard H. Walters of the University of Waterloo in Ontario found experimentally that male hospital attendants who had been shown a movie of a knife fight generally administered more severe punishment to another person soon afterward than did other attendants who had seen a more innocuous movie. The men in this experiment were shown one of the two movie scenes and then served for what was supposedly a study of the effects of punishment. They were to give an electric shock to someone else in the room with them each time the person made a mistake on a learning task. The intensity of the electric shocks could be varied. This other person, who was actually the experimenter's confederate, made a constant number of mistakes, but the people who had seen the knife fight gave him more intense punishment than the men who had witnessed the nonaggressive film. The filmed violence had apparently aroused aggressive tendencies in the men and, since the situation allowed the expression of aggression, their tendencies were readily translated into severe aggressive actions.

These experiments, taken together with our findings, suggest a change in approach to the manner in which screenplays make their moral point. Although it may be socially desirable for a villain to receive his just deserts at the end of a motion picture, it would seem equally desirable that this retribution should not take the form of physical aggression.

The key point to be made about aggressiveness on the basis of experimentation in this area is that a person's hostile tendencies will persist, in spite of any satisfaction he may derive from filmed violence, to the extent that his frustrations and aggressive habits persist. There is no free-floating aggressive energy that can be released through a wide range of different activities. A drive to hurt cannot be reduced through attempts to master other drives, as Freud proposed, or by observing others as they act aggressively.

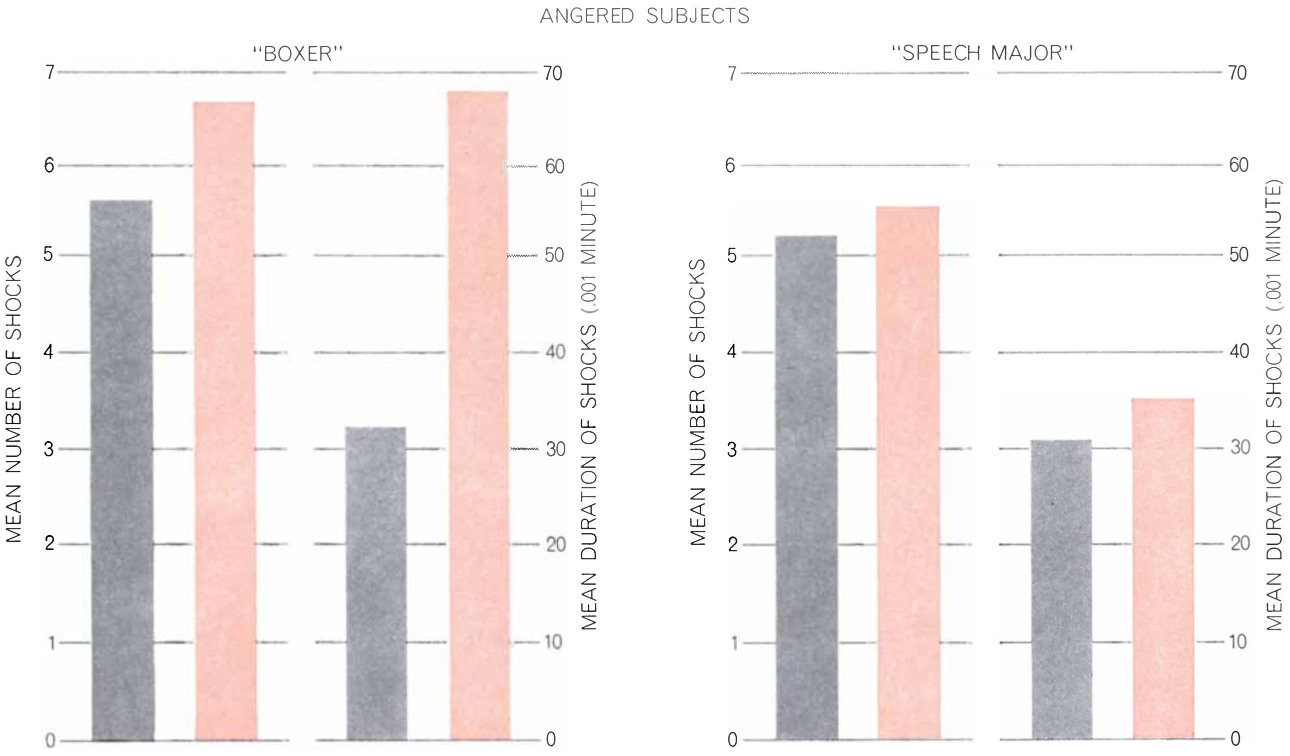
In fact, there have been studies suggesting that even if the angered person performs the aggression himself, his hostile inclinations are not satisfied unless he believes he has attacked his tormentor and not someone else. J. E. Hokanson of Florida State University has shown that angered subjects permitted to commit aggression against the person who had annoyed them often display a drop in systolic blood pressure. They seem to have experienced a physiological relaxation, as if they had satisfied their aggressive urges. Systolic pressure declines less, however, when the angered people carry out the identical motor activity involved in the aggression but without believing they have attacked the source of their frustration.

I must now qualify some of the observations I have made. Many aggressive motion pictures and television programs



SUBJECT	A	B	C	D	E	F	G	H
NUMBER OF SHOCKS	6	3	8	3	6	7	5	4
DURATION (.001 MINUTE)	46	38	76	10	120	49	60	28

TASK BY ANNOYING CO-WORKER supposedly was to draw a floor plan. Actually each subject saw the floor plan shown here. The subject was asked to judge the creativeness of the plan and to record his opinion by pressing a telegraph key that he thought would give electric shocks to the co-worker: one shock for a good job and more for poor work. Responses of eight subjects who saw prizefight film are shown; those in color represent men told that Douglas deserved his beating; those in black, men informed it was undeserved.



CO-WORKER'S INTRODUCTION also produced variations in aggressiveness of subjects. Co-worker was introduced as boxer or as speech major; reactions shown here are of men who were angered by co-worker and then saw either a fight film (*colored bars*) or a neutral film (*gray bars*). Co-worker received strongest attacks when subjects presumably associated him with fight film.

have been presented to the public, but the number of aggressive incidents demonstrably attributable to such shows is quite low. One explanation for this is that most social situations, unlike the conditions in the experiments I have described, impose constraints on aggression. People are usually aware of the social norms prohibiting attacks on others, consequently they inhibit whatever hostile inclinations might have been aroused by the violent films they have just seen.

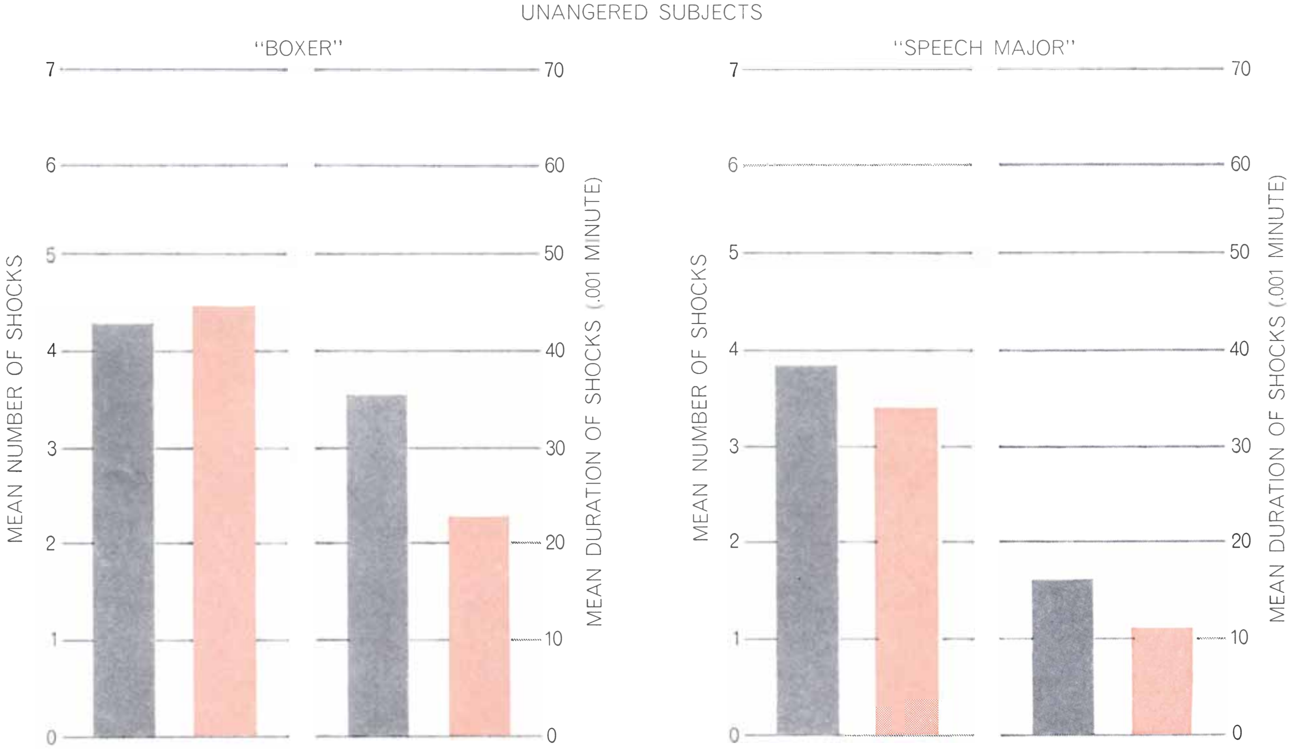
Another important factor is the attributes of the people encountered by a person after he has viewed filmed violence. A man who is emotionally aroused does not necessarily attack just anyone. Rather, his aggression is directed toward specific objectives. In other words, only certain people are capable of drawing aggressive responses from him. In my theoretical analyses of the sources of aggressive behavior I have suggested that the arousal of anger only creates a readiness for aggression. The theory holds that whether or not this predisposition is translated into actual aggression depends on the presence of appropriate cues: stimuli associated with the present or previous instigators of anger. Thus if someone has been insulted, the sight or the thought of others who have provoked him, whether then or earlier, may evoke hostile responses from him.

An experiment I conducted in conjunction with a graduate student provides some support for this train of thought. People who had been deliberately provoked by the experimenter were put to work with two other people, one a person who had angered them earlier and the other a neutral person. The subjects showed the greatest hostility, following their frustration by the experimenter, to the co-worker they disliked. He, by having thwarted them previously, had acquired the stimulus quality that caused him to draw aggression from them after they had been aroused by the experimenter.

My general line of reasoning leads me to some predictions about aggressive behavior. In the absence of any strong inhibitions against aggression, people who have recently been angered and have then seen filmed aggression will be more likely to act aggressively than people who have not had those experiences. Moreover, their strongest attacks will be directed at those who are most directly connected with the provocation or at others who either have close associations with the aggressive motion picture or are disliked for any reason.

One of our experiments showed results consistent with this analysis. In this study male college students, taken separately, were first either angered or not angered by *A*, one of the two graduate students acting as experimenters. *A* had been introduced earlier either as a college boxer or as a speech major. After *A* had had his session with the subject, *B*, the second experimenter, showed the subject a motion picture: either the prizefight scene mentioned earlier or a neutral film. (One that we used was about canal boats in England; the other, about the travels of Marco Polo.)

We hypothesized that the label "college boxer" applied to *A* in some of the cases would produce a strong association in the subject's mind between *A* and the boxing film. In other words, any aggressive tendencies aroused in the subject would be more likely to be directed at *A* the college boxer than at *A* the speech major. The experiment bore out this hypothesis. Using questionnaires at the end of the session as the measures of hostility, we found that the deliberately angered subjects directed more hostility at *A*, the source of their anger, when they had seen the fight film and he had been identified as a boxer. Angered men who had seen the



SIMILAR TEST, varied by the fact that the co-worker behaved neutrally toward the subjects and therefore presumably did not anger them, produced these reactions. The greater number of shocks given to the co-worker introduced as a boxer than to the one introduced as a speech major apparently reflected a tendency to take a generally negative attitude toward persons identified as boxers.

neutral film showed no particular hostility to *A* the boxer. In short, the insulting experimenter received the strongest verbal attacks when he was also associated with the aggressive film. It is also noteworthy that in this study the boxing film did not influence the amount of hostility shown toward *A* when he had not provoked the subjects.

A somewhat inconsistent note was introduced by our experiments, described previously, in "physiological reactions." Here the nonangered groups, regardless of which film they saw, gave the confederate more and longer shocks when they thought he was a boxer than when they understood him to be a speech major [*see illustration above*]. To explain this finding I assume that our subjects had a negative attitude toward boxers in general. This attitude may have given the confederate playing the role of boxer the stimulus quality that caused him to draw aggression from the angered subjects. But it could only have been partially responsible, since the insulted subjects who saw the neutral film gave fewer shocks to the boxer than did the insulted subjects who saw the prizefight film.

Associations between the screen and the real world are important. People seem to be emotionally affected by a screenplay to the extent that they associate the events of the drama with their own life experiences. Probably adults are less strongly influenced than children because they are aware that the film is make-believe and so can dissociate it from their own lives. Still, it seems clear from the experiments I have described that an aggressive film can induce aggressive actions by anyone in the audience. In most instances I would expect that effect to be short-lived. The emotional reaction produced by filmed violence probably dies away rather rapidly as the viewer enters new situations and encounters new stimuli. Subjected to different influences, he becomes less and less ready to attack other people.

Television and motion pictures, however, may also have some persistent effects. If a young child sees repeatedly that screen heroes gain their ends through aggressive actions, he may conclude that aggression is desirable behavior. Fortunately screenplays do not consistently convey that message, and in any event the child is exposed to many other cultural norms that discourage aggression.

As I see it, the major social danger inherent in filmed violence has to do with the temporary effects produced in a fairly short period immediately following the film. For that period, at least, a person—whether an adult or a child—who had just seen filmed violence might conclude that he was warranted in attacking those people in his own life who had recently frustrated him. Further, the film might activate his aggressive habits so that for the period of which I speak he would be primed to act aggressively. Should he then encounter people with appropriate stimulus qualities, people he dislikes or connects psychologically with the film, this predisposition could lead to open aggression.

What, then, of catharsis? I would not deny that it exists. Nor would I reject the argument that a frustrated person can enjoy fantasy aggression because he sees characters doing things he wishes he could do, although in most cases his inhibitions restrain him. I believe, however, that effective catharsis occurs only when an angered person perceives that his frustrater has been aggressively injured. From this I argue that filmed violence is potentially dangerous. The motion picture aggression has increased the chance that an angry person, and possibly other people as well, will attack someone else.

The Stereochemical Theory of Odor

There is evidence that the sense of smell is based on the geometry of molecules. Seven primary odors are distinguished, each of them by an appropriately shaped receptor at the olfactory nerve endings

by John E. Amoore, James W. Johnston, Jr., and Martin Rubin

A rose is a rose and a skunk is a skunk, and the nose easily tells the difference. But it is not so easy to describe or explain this difference. We know surprisingly little about the sense of smell, in spite of its important influence on our daily lives and the voluminous literature of research on the subject. One is hard put to describe an odor except by comparing it to a more familiar one. We have no yardstick for measuring the strength of odors, as we measure sound in decibels and light in lumens. And we have had no satisfactory general theory to explain how the nose and brain detect, identify and recognize an odor. More than 30 different theories have been suggested by investigators in various disciplines, but none of them has passed the test of experiments designed to determine their validity.

The sense of smell obviously is a chemical sense, and its sensitivity is proverbial; to a chemist the ability of the nose to sort out and characterize substances is almost beyond belief. It deals with complex compounds that might take a chemist months to analyze in the laboratory; the nose identifies them instantly, even in an amount so small (as little as a ten-millionth of a gram) that the most sensitive modern laboratory instruments often cannot detect the substance, let alone analyze and label it.

Two thousand years ago the poet Lucretius suggested a simple explanation of the sense of smell. He speculated that the "palate" contained minute pores of various sizes and shapes. Every odorous substance, he said, gave off tiny "molecules" of a particular shape, and the odor was perceived when these molecules entered pores in the palate. Presumably the identification of each odor depended on which pores the molecules fitted.

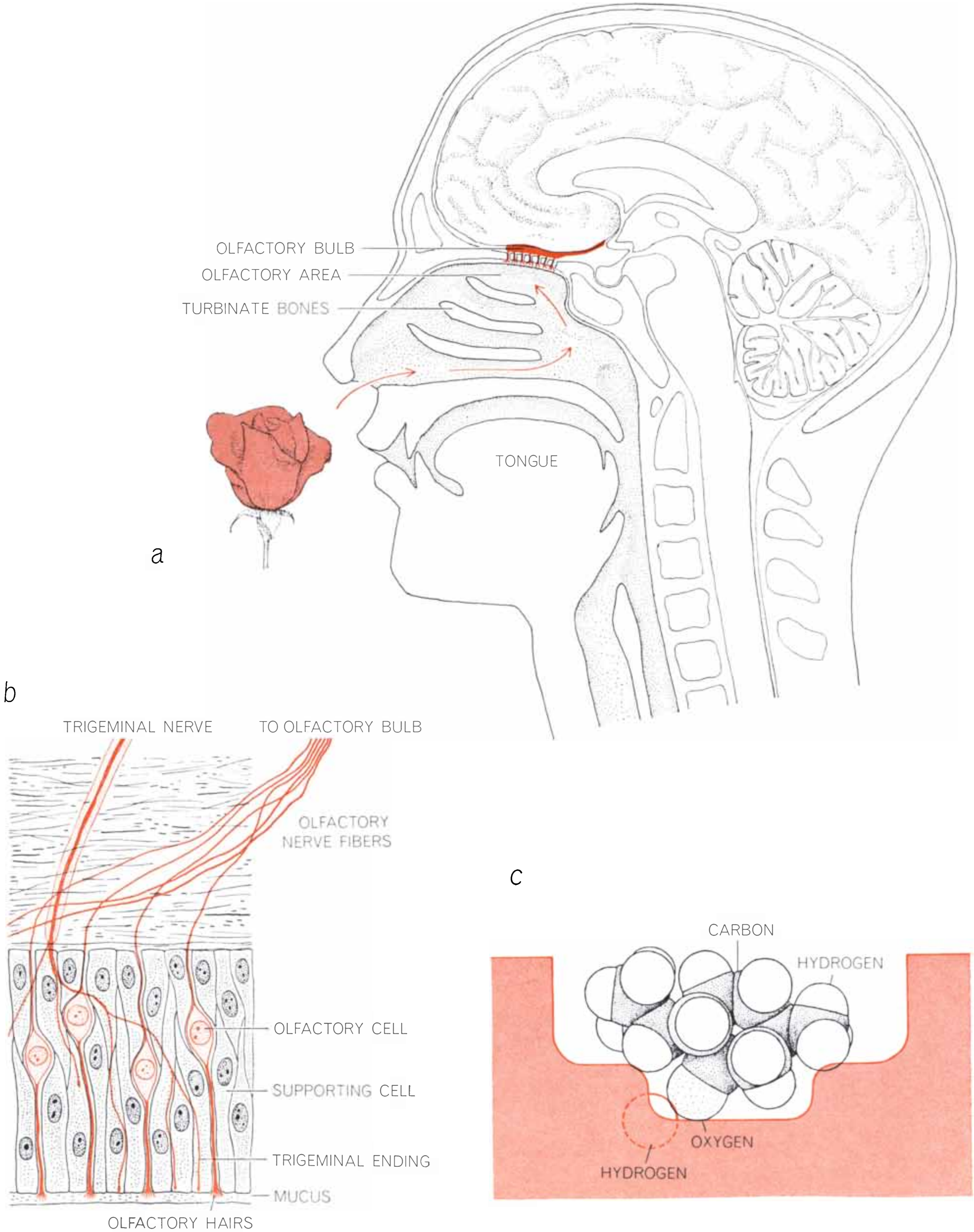
It now appears that Lucretius' guess was essentially correct. Within the past few years new evidence has shown rather convincingly that the geometry of molecules is indeed the main determinant of odor, and a theory of the olfactory process has been developed in modern terms. This article will discuss the stereochemical theory and the experiments that have tested it.

The nose is always on the alert for odors. The stream of air drawn in through the nostrils is warmed and filtered as it passes the three baffle-shaped turbinate bones in the upper part of the nose; when an odor is detected, more of the air is vigorously sniffed upward to two clefts that contain the smelling organs [*see illustration on opposite page*]. These organs consist of two patches of yellowish tissue, each about one square inch in area. Embedded in the tissue are two types of nerve fiber whose endings receive and detect the odorous molecules. The chief type is represented by the fibers of the olfactory nerve; at the end of each of these fibers is an olfactory cell bearing a cluster of hairlike filaments that act as receptors. The other type of fiber is a long, slender ending of the trigeminal nerve, which is sensitive to certain kinds of molecules. On being stimulated by odorous molecules, the olfactory nerve endings send signals to the olfactory bulb and thence to the higher brain centers where the signals are integrated and interpreted in terms of the character and intensity of the odor.

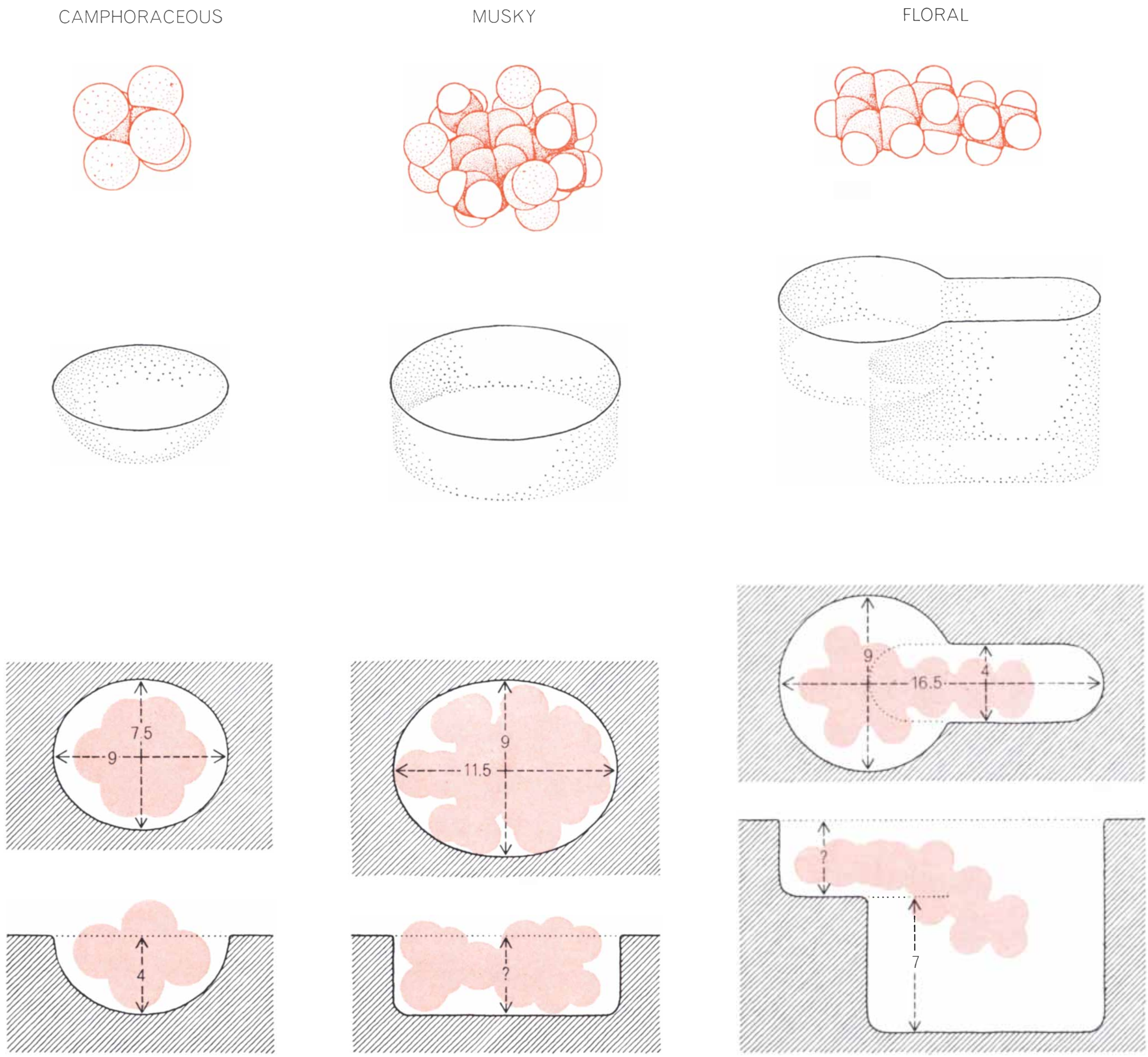
From the nature of this system it is obvious at once that to be smelled at all a material must have certain basic properties. In the first place, it must be volatile. A substance such as onion soup, for example, is highly odorous because it continuously gives off vapor that can reach the nose (unless the soup is im-

PRIMARY ODOR	CHEMICAL EXAMPLE	FAMILIAR SUBSTANCE
CAMPHORACEOUS	CAMPHOR	MOTH REPELLENT
MUSKY	PENTADECANOLACTONE	ANGELICA ROOT OIL
FLORAL	PHENYLETHYL METHYL ETHYL CARBINOL	ROSES
PEPPERMINTY	MENTHONE	MINT CANDY
ETHEREAL	ETHYLENE DICHLORIDE	DRY-CLEANING FLUID
PUNGENT	FORMIC ACID	VINEGAR
PUTRID	BUTYL MERCAPTAN	BAD EGG

PRIMARY ODORS identified by the authors are listed, together with chemical and more familiar examples. Each of the primary odors is detected by a different receptor in the nose. Most odors are composed of several of these primaries combined in various proportions.



ANATOMY of the sense of smell is traced in these drawings. Air carrying odorous molecules is sniffed up past the three baffle-shaped turbinate bones to the olfactory area (*a*), patches of epithelium in which are embedded the endings of large numbers of olfactory nerves (*color*). A microscopic section of the olfactory epithelium (*b*) shows the olfactory nerve cells and their hairlike endings, trigeminal endings and supporting cells. According to the stereochemical theory different olfactory nerve cells are stimulated by different molecules on the basis of the size and shape or the charge of the molecule; these properties determine which of various pits and slots on the olfactory endings it will fit. A molecule of *l*-menthone is shown fitted into the "pepperminty" cavity (*c*).



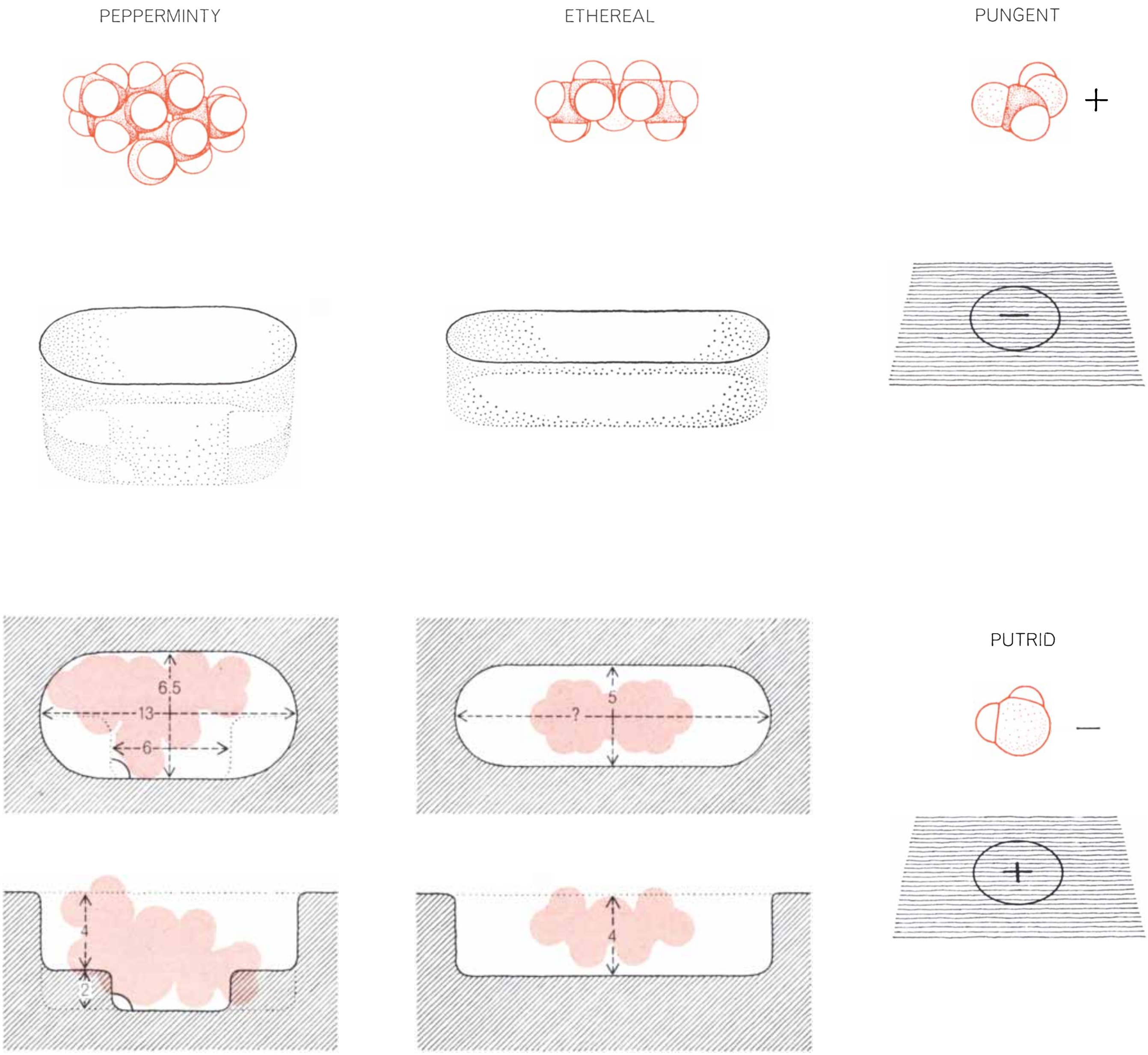
OLFACTORY RECEPTOR SITES are shown for each of the primary odors, together with molecules representative of each odor. The shapes of the first five sites are shown in perspective and (with the molecules silhouetted in them) from above and the side;

prisoned in a sealed can). On the other hand, at ordinary temperatures a substance such as iron is completely odorless because it does not evaporate molecules into the air.

The second requirement for an odorous substance is that it should be soluble in water, even if only to an almost infinitesimal extent. If it is completely insoluble, it will be barred from reaching the nerve endings by the watery film that covers their surfaces. Another common property of odorous materials is solubility in lipids (fatty substances); this enables them to penetrate the nerve endings through the lipid layer that forms part of the surface membrane of every cell.

Beyond these elementary properties the characteristics of odorous materials have been vague and confusing. Over the years chemists empirically synthesized a wealth of odorous compounds, both for perfumers and for their own studies of odor, but instead of clarifying the properties responsible for odor these compounds seemed merely to add to the confusion. A few general principles were discovered. For instance, it was found that adding a branch to a straight chain of carbon atoms in a perfume molecule markedly increased the potency of the perfume. Strong odor also seemed to be associated with chains of four to eight carbon atoms in the molecules of certain alcohols and aldehydes. The more chemists analyzed the chemical structure of odorous substances, however, the more puzzles emerged. From the standpoint of chemical composition and structure the substances showed some remarkable inconsistencies.

Curiously enough, the inconsistencies themselves began to show a pattern. As an example, two optical isomers—molecules identical in every respect except that one is the mirror image of the other—may have different odors. As another



known dimensions are given in angstrom units. The molecules are (*left to right*) hexachloroethane, xylene musk, alpha-amylpyridine, *l*-menthol and diethyl ether. Pungent (formic acid) and putrid (hydrogen sulfide) molecules fit because of charge, not shape.

example, in a compound whose molecules contain a small six-carbon-atom benzene ring, shifting the position of a group of atoms attached to the ring may sharply change the odor of the compound, whereas in a compound whose molecules contain a large ring of 14 to 19 members the atoms can be rearranged considerably without altering the odor much. Chemists were led by these facts to speculate on the possibility that the primary factor determining the odor of a substance might be the over-all geometric shape of the molecule rather than any details of its composition or structure.

In 1949 R. W. Moncrieff in Scotland gave form to these ideas by proposing a hypothesis strongly reminiscent of the 2,000-year-old guess of Lucretius. Moncrieff suggested that the olfactory system is composed of receptor cells of a few different types, each representing a distinct "primary" odor, and that odorous molecules produce their effects by fitting closely into "receptor sites" on these cells. His hypothesis is an application of the "lock and key" concept that has proved fruitful in explaining the interaction of enzymes with their substrates, of antibodies with antigens and of deoxyribonucleic acid with the "messenger" ribonucleic acid that presides at the synthesis of protein.

To translate Moncrieff's hypothesis into a practical approach for investigating olfaction, two specific questions had to be answered. What are the "primary odors"? And what is the shape of the receptor site for each one? To try to find answers to these questions, one of us (Amoore, then at the University of Oxford) made an extensive search of the literature of organic chemistry, looking for clues in the chemical characteristics of odorous compounds. His search resulted in the conclusion that there were seven primary odors, and in 1952 his findings were summed up in a stereochemical theory of olfaction that identified the seven odors and gave a detailed description of the size, shape and chemical affinities of the seven corresponding receptor sites.

To identify the primary odors Amoore started with the descriptions of 600 organic compounds noted in the literature as odorous. If the receptor-site hypothesis was correct, the primary odors should be recognized much more frequently than mixed odors made up of two or more primaries. And indeed, in the chemists' descriptions certain odors turned up much more commonly than others. For instance, the descriptions mentioned more than 100 compounds as having a camphor-like odor, whereas only about half a dozen were put in the category characterized by the odor of cedarwood. This suggested that in all likelihood the camphor odor was a primary one. By this test of frequency, and from other considerations, it was possible to select seven odors that stand out as probable primaries. They are: camphoraceous, musky, floral, pepperminty, ethereal (ether-like), pungent and putrid.

From these seven primaries every known odor could be made by mixing them in certain proportions. In this respect the primary odors are like the three primary colors (red, green and blue) and the four primary tastes (sweet, salt, sour and bitter).

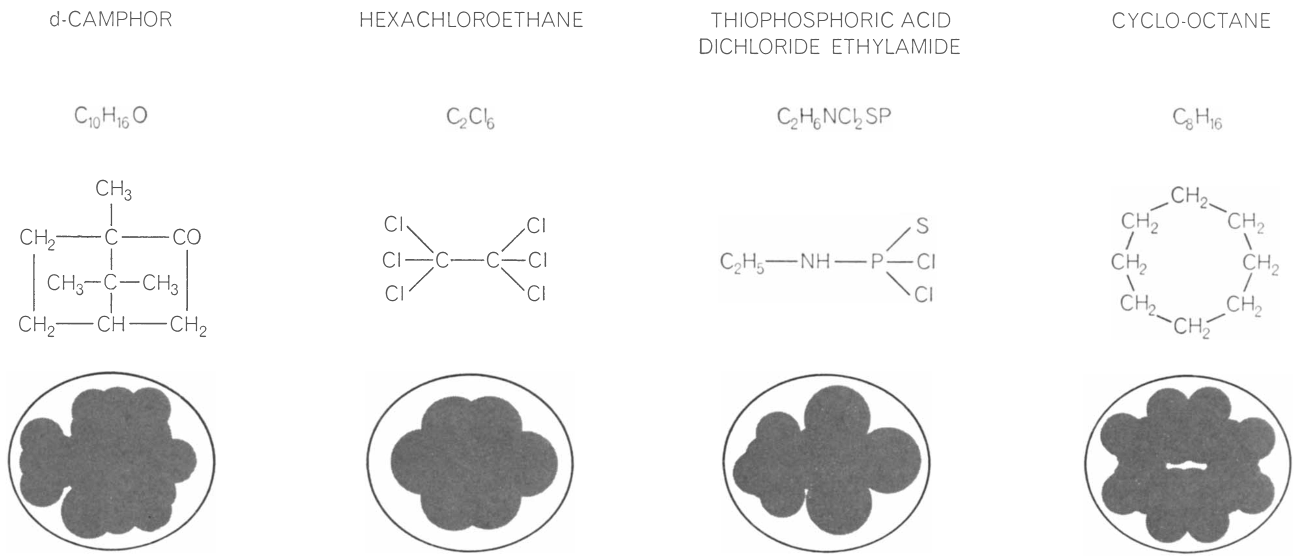
To match the seven primary odors there must be seven different kinds of olfactory receptors in the nose. We can picture the receptor sites as ultramicroscopic slots or hollows in the nerve-fiber membrane, each of a distinctive shape and size. Presumably each will accept a molecule of the appropriate configuration, just as a socket takes a plug. Some molecules may be able to fit into two different sockets—broadside into a wide receptor or end on into a narrow one. In such cases the substance, with its molecules occupying both types of receptor, may indicate a complex odor to the brain.

The next problem was to learn the shapes of the seven receptor sites. This was begun by examining the structural formulas of the camphoraceous compounds and constructing models of their molecules. Thanks to the techniques of modern stereochemistry, which explore the structure of molecules with the aid of X-ray diffraction, infrared spectroscopy, the electron-beam probe and other means, it is possible to build a three-dimensional model of the molecule of any chemical compound once its structural formula is known. There are rules for building these models; also available are building blocks (sets of atomic units) on a scale 100 million times actual size.

As the models of the camphoraceous molecules took form, it soon became clear that they all had about the same shape: they were roughly spherical. Not only that, it turned out that when the models were translated into molecular dimensions, all the molecules also had about the same diameter: approximately seven angstrom units. (An angstrom unit is a ten-millionth of a millimeter.) This meant that the receptor site for camphoraceous molecules must be a hemispherical bowl about seven angstroms in diameter. Many of the camphoraceous molecules are rigid spheres that would inevitably fit into such a bowl; the others are slightly flexible and could easily shape themselves to the bowl.

When other models were built, shapes and sizes of the molecules representing the other primary odors were found [*see illustration on preceding two pages*]. The musky odor is accounted for by molecules with the shape of a disk about 10 angstroms in diameter. The pleasant floral odor is caused by molecules that have the shape of a disk with a flexible tail attached—a shape somewhat like a kite. The cool pepperminty odor is produced by molecules with the shape of a wedge, and with an electrically polarized group of atoms, capable of forming a hydrogen bond, near the point of the wedge. The ethereal odor is due to rod-shaped or other thin molecules. In each of these cases the receptor site in the nerve endings presumably has a shape and size corresponding to those of the molecule.

The pungent and putrid odors seem to be exceptions to the Lucretian scheme of shape-matching. The molecules responsible for these odors are of indifferent shapes and sizes; what matters in their case is the electric charge of the molecule. The pungent class of odors is produced by compounds whose molecules, because of a deficiency of electrons, have a positive charge and a strong affinity for electrons; they are called electrophilic. Putrid odors, on the other hand, are caused by molecules



UNRELATED CHEMICALS with camphor-like odors show no resemblance in empirical formulas and little in structural formulas. **Yet, because the size and shape of their molecules are similar, they all fit the bowl-shaped receptor for camphoraceous molecules.**

that have an excess of electrons and are called nucleophilic, because they are strongly attracted by the nuclei of adjacent atoms.

A theory is useful only if it can be tested in some way by experiment. One of the virtues of the stereochemical theory is that it suggests some very specific and unambiguous tests. It has been subjected to six severe tests of its accuracy so far and has passed each of them decisively.

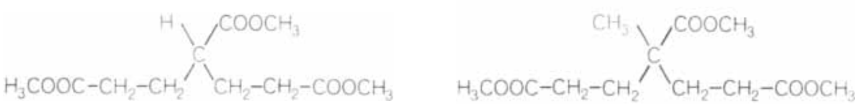
To start with, it is at once obvious that from the shape of a molecule we should be able to predict its odor. Suppose, then, that we synthesize molecules of certain shapes and see whether or not they produce the odors predicted for them.

Consider a molecule consisting of three chains attached to a single carbon atom, with the central atom's fourth bond occupied only by a hydrogen atom [*see top illustration at right*]. This molecule might fit into a kite-shaped site (floral odor), a wedge-shaped site (pepperminty) or, by means of one of its chains, a rod-shaped site (ethereal). The theory predicts that the molecule should therefore have a fruity odor composed of these three primaries. Now suppose we substitute the comparatively bulky methyl group (CH_3) in place of the small hydrogen atom at the fourth bond of the carbon atom. The introduction of a fourth branch will prevent the molecule from fitting so easily into a kite-shaped or wedge-shaped site, but one of the branches should still be able to occupy a rod-shaped site. As a result, the theory predicts, the ether smell should now predominate.

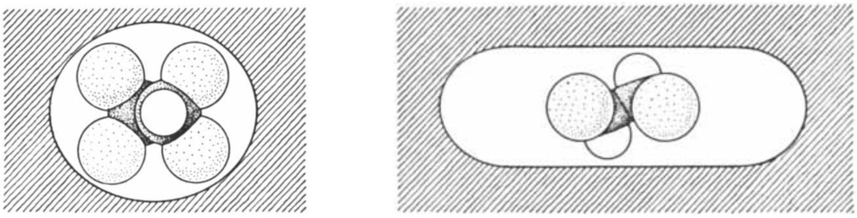
Another of us (Rubin) duly synthesized the two structures in his laboratory at the Georgetown University School of Medicine. The third author (Johnston), also working at the Georgetown School of Medicine, then submitted the products to a panel of trained smellers. He used an instrument called the olfactometer, which by means of valves and controlled air streams delivers carefully measured concentrations of odors, singly or mixed, to the observer. The amount of odorous vapor delivered was measured by gas chromatography. A pair of olfactometers was used, one for each of the two compounds under test, and the observer was asked to sniff alternately from each.

The results verified the predictions. The panel reported that Compound A had a fruity (actually grapelike) odor, and that Compound B, with the methyl group substituted for the hydrogen atom, had a pronounced tinge of the ether-like odor. This experiment, and the theory behind it, make understandable the earlier finding that the odor of certain benzene-ring compounds changes sharply when the position of a group of atoms is shifted. The change in odor is due to the change in the over-all shape of the molecule.

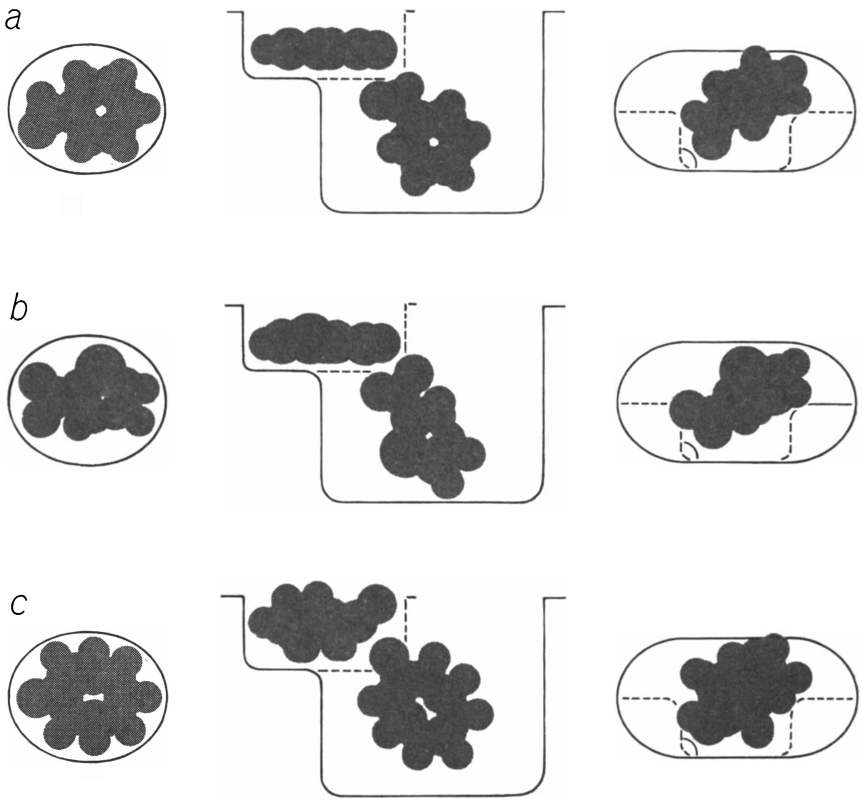
A second test suggested itself. Could a complex odor found in nature be matched by putting together a combination of primary odors? Taking the odor of cedarwood oil as a test case, Amoore found that chemicals known to



CHANGE IN SHAPE of a molecule changed its odor. The molecule at left smelled fruity because it fitted into three sites. When it was modified (*right*) by the substitution of a methyl group for a hydrogen, it smelled somewhat ethereal. Presumably the methyl branch made it fit two of the original sites less well but allowed it still to fit the ethereal slot.



SINGLE CHEMICAL has more than one primary odor if its molecule can fit more than one site. Acetylenetetrabromide, for example, is described as smelling both camphoraceous and ethereal. It turns out that its molecule can fit either site, depending on how it lies.



COMPLEX ODORS are made up of several primaries. Three molecules with an almond odor are illustrated: benzaldehyde (*a*), alpha-nitrothiophen (*b*) and cyclo-octanone (*c*). Each of them fits (*left to right*) camphoraceous, floral (with two molecules) and pepperminty sites.

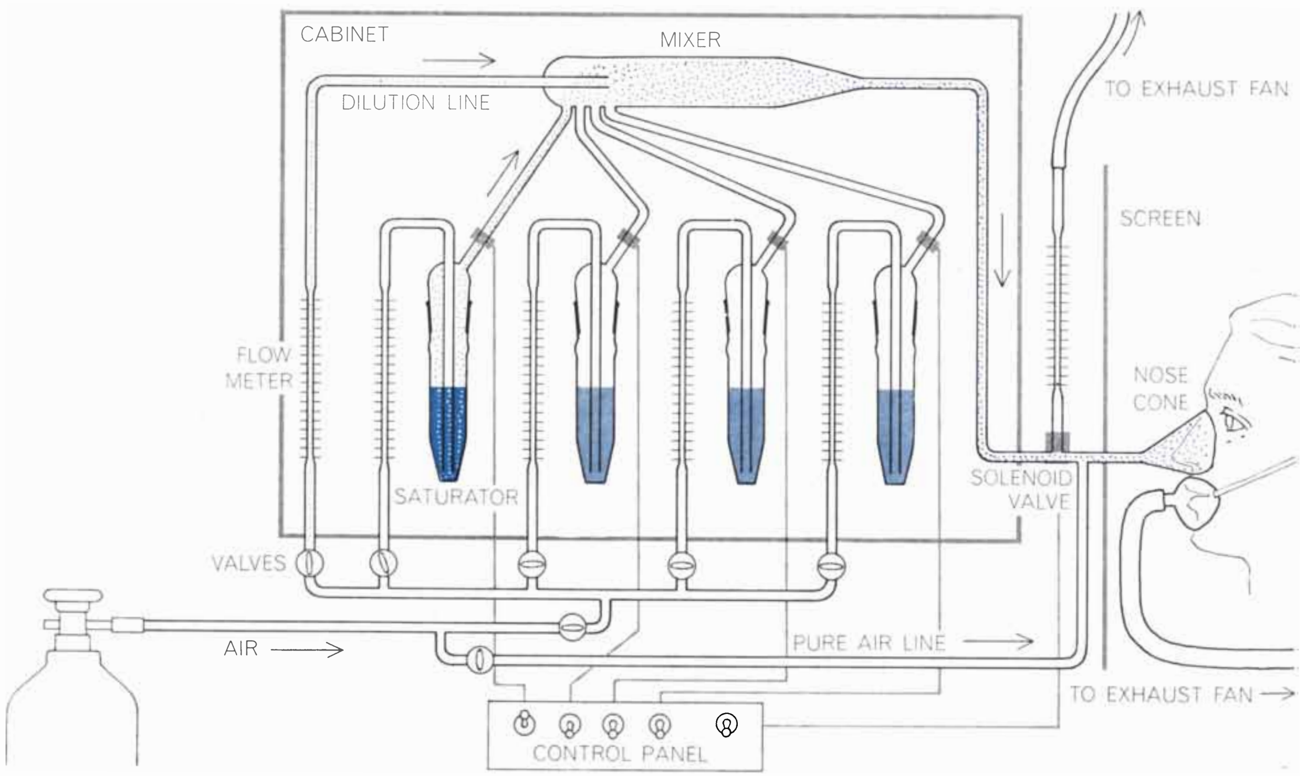
possess this odor had molecular shapes that would fit into the receptor sites for the camphoraceous, musky, floral and pepperminty odors. Johnston proceeded to try various combinations of these four primaries to duplicate the cedarwood odor. He tested each mixture on eight trained observers, who compared the synthetic odor with that of cedarwood oil. After 86 attempts he was able to produce a blend that closely matched the natural cedarwood odor. With the same four primaries he also succeeded in synthesizing a close match for the odor of sandalwood oil.

The next two tests had to do with the identification of pure (that is, primary) odors. If the theory was correct, a molecule that would fit only into a receptor site of a particular shape and size, and no other, should represent a primary odor in pure form. Molecules of the same shape and size should smell very much alike; those of a different primary shape should smell very different. Human subjects were tested on this point. Presented with the odors from a pair of different substances whose molecules nonetheless had the same primary shape (for example, that of the floral odor), the subjects judged the two odors to be highly similar to each other. When the pair of substances presented had the pure molecular traits of different categories (for instance, the kite shape of the floral odor and the nucleophilic charge characteristic of putrid compounds), the subjects found the odors extremely dissimilar.

Johnston went on to make the same sort of test with honeybees. He set up an experiment designed to test their ability to discriminate between two odors, one of which was "right" (associated with sugar sirup) and the other "wrong" (associated with an electric shock). The pair of odors might be in the same primary group or in different primary groups (for example, floral and pepperminty). At pairs of scented vials on a table near the hive, the bees were first conditioned to the fact that one odor of a pair was right and the other was wrong. Then the sirup bait in the vials was replaced with distilled water and freshly deodorized scent vials were substituted for those used during the training period. The visits of the marked bees to the respective vials in search of sirup were counted. It could be assumed that they would tend to visit the odor to which they had been favorably conditioned and to avoid the one that had been associated with electric shock, provided that they could distinguish between the two.

So tested, the honeybees clearly showed that they had difficulty in detecting a difference between two scents within the same primary group (say pepperminty) but were able to distinguish easily between different primaries (pepperminty and floral). In the latter case they almost invariably chose the correct scent without delay. These experiments indicate that the olfactory system of the honeybee, like that of human beings, is based on the stereochemical principle, although the bee's smelling organ is different; it smells not with a nose but with antennae. Apparently the receptor sites on the antennae are differentiated by shape in the same way as those in the human nose.

A fifth test was made with human observers trained in odor discrimination. Suppose they were presented with a number of substances that were very different chemically but whose molecules had about the same over-all shape. Would all these dissimilar compounds smell alike? Five compounds were used for the test. They belonged to three different chemical families differing radically from one another in the internal structure of their molecules but in all five cases had the disk shape characteristic of the molecules of musky-odored substances. The observers, exposed to



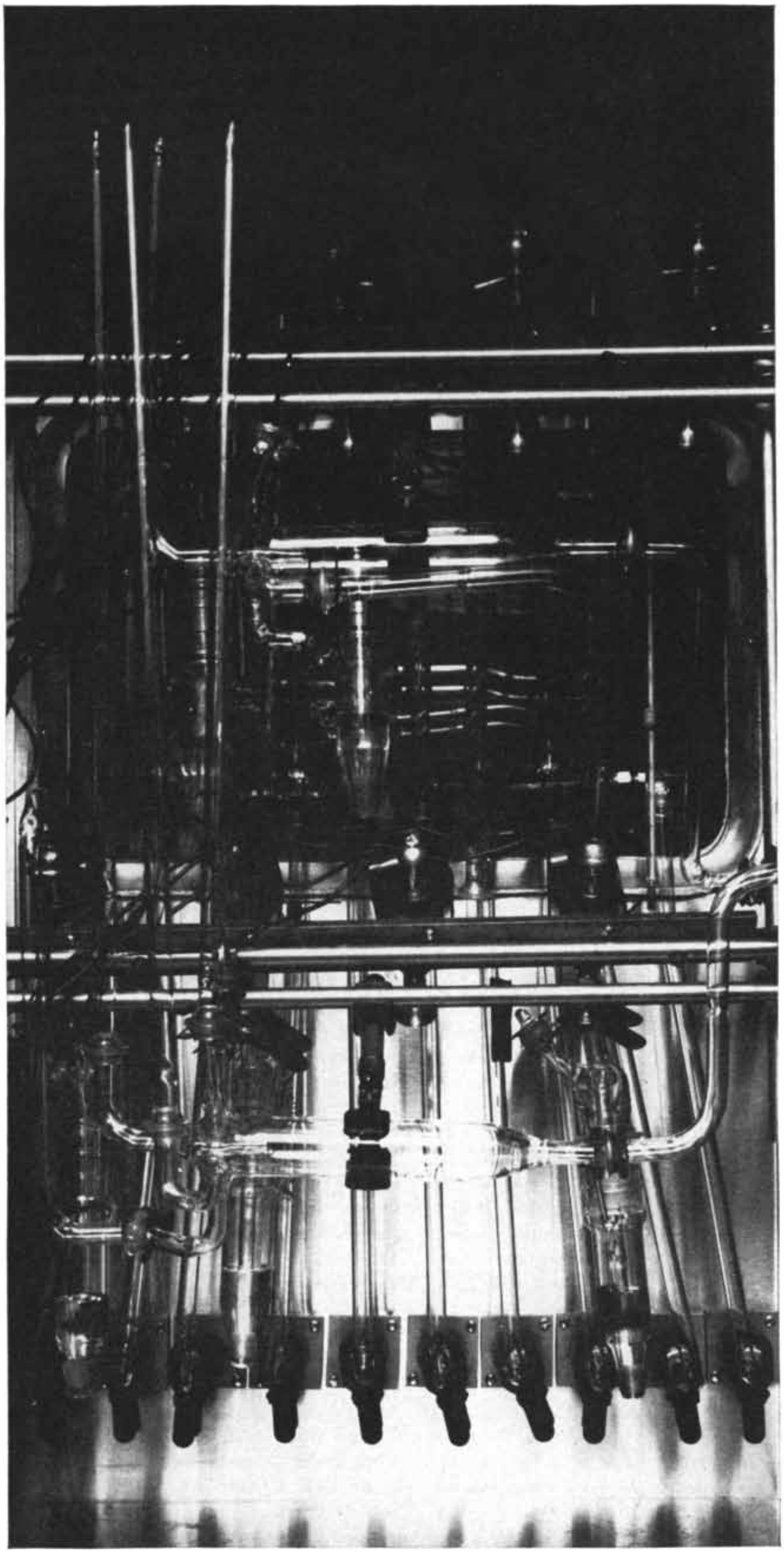
OLFACTOMETER developed by one of the authors (Johnston) mixes odors in precise proportions and delivers them to a nose cone for sampling. This schematic diagram shows the main elements. Air bubbles through a liquid in one of the saturators, picks up odorous molecules and is then diluted with pure air or mixed with air carrying other odors. The experimenter controls the solenoid valves.

the vapors of these five chemicals among many others by means of the olfactometer, did indeed pick out and identify all five as musky. By the odor test, however, they were often unable to distinguish these five quite different chemicals from one another.

Basically all this evidence in favor of the stereochemical theory was more or less indirect. One would like some sort of direct proof of the actual existence of differentiated receptor sites in the smelling organ. Recently R. C. Gesteland, then at the Massachusetts Institute of Technology, searched for such evidence. He devised a way to tap the electric impulses from single olfactory-nerve cells by means of microelectrodes. Applying his electrodes to the olfactory organ of the frog, Gesteland presented various odors to the organ and tapped the olfactory cells one by one to see if they responded with electric impulses. He found that different cells responded selectively to different odors, and his exploration indicated that the frog has about eight such different receptors. What is more, five of these receivers correspond closely to five of the odors (camphoraceous, musky, ethereal, pungent and putrid) identified as primary in the stereochemical theory! This finding, then, can be taken as a sixth and independent confirmation of the theory.

Equipped now with a tested basic theory to guide further research, we can hope for much faster progress in the science of osmics (smell) than has been possible heretofore. This may lead to unexpected benefits for mankind. For man the sense of smell may perhaps have become less essential as a life-and-death organ than it is for lower animals, but we still depend on this sense much more than we realize. One can gain some appreciation of the importance of smell to man by reflecting on how tasteless food becomes when the nose is blocked by a head cold and on how unpleasantly we are affected by a bad odor in drinking water or a closed room. Control of odor is fundamental in our large perfume, tobacco and deodorant industries. No doubt odor also affects our lives in many subtle ways of which we are not aware.

The accelerated research for which the way is now open should make it possible to analyze in fine detail the complex flavors in our food and drink, to get rid of obnoxious odors, to develop new fragrances and eventually to synthesize any odor we wish, whether to defeat pests or to delight the human nose.



CONSTANT-TEMPERATURE CABINET maintains the olfactometer parts at 77 degrees Fahrenheit. The photograph shows the interior of the cabinet, containing two units of the type diagramed on the opposite page. Several of the saturators are visible, as are two mixers (*horizontal glass vessels*), each of them connected by tubing to a nose cone at right.

Tektites and Impact Fragments from the Moon

It has been argued that the glassy stones called tektites arose from the impact of huge meteorites on the earth. There are also arguments that they originated with similar impacts on the moon

by John A. O'Keefe

The earth is undoubtedly strewn with millions of tons of rock and dust from the surface of the moon. Although most of this lunar material has not been recognized, possibly because it bears a close resemblance to terrestrial rocks, certain small glassy stones that have been extensively studied by geologists and geophysicists may well be part of the lunar debris. These are the tektites, found in "strewn fields" in North America, the Far East, Europe and Africa.

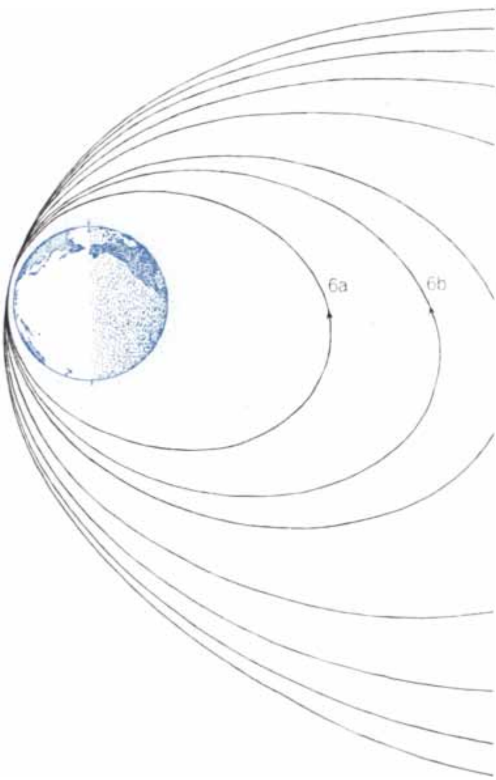
Before the tektites came to earth they were melted by high-speed passage through the atmosphere; then they solidified, many of them in the shape of drops, and some of them were curiously sculptured by the air stream as they fell to the ground. One school of thought holds that tektites are stones thrown up by the impact of huge meteorites on the earth [see "Tektites," by Virgil E. Barnes; SCIENTIFIC AMERICAN, November, 1961]. I am among those who believe that these intriguing objects came from the impact of meteorites on the moon. As I shall explain, this view leads to some striking conclusions: that the moon has a hot interior and is differentiated into a crust and a mantle (although it has no molten core), and that the moon is not a small planet "captured" by the earth but is either a chunk of the primordial earth or a twin of the earth, formed at the same time from the same batch of materials.

Many geophysicists believe that the earth constantly receives debris from the moon simply because meteorites frequently strike the moon and the moon has no atmosphere to cushion their fall. Even the smallest meteorites crash into it with all the velocity they possessed in space. At a typical meteorite velocity, of the order of 17 kilometers per second, an impact produces an explosion that digs a crater and hurls out a considerable amount of debris. The craters can range in size, depending on the size of the meteorite, from the large structures visible in telescopes down to holes so small that the loose "fuzz" of the moon's surface traps the ejected dust.

The minimum speed of an object falling on the moon is 2.4 kilometers per second; an object thrown up from the moon at the same velocity or a higher one will escape into space. Laboratory experiments have shown that some of the debris from any high-velocity impact will acquire a speed greater than that of the impacting object. This means that matter will escape from the moon every time it is hit. In fact, recent calculations by Eugene M. Shoemaker of the U.S. Geological Survey and Donald E. Gault of the National Aeronautics and Space Administration Ames Research Center at Moffett Field, Calif., suggest that the amount of material leaving the moon actually exceeds the amount arriving!

Investigators at the Ames Center and at the NASA Goddard Space Flight Center in Greenbelt, Md., have calculated that most of this matter goes into orbit around the sun. At the moon's distance from the earth an object in space needs a velocity of only 1.5 kilometers per second to escape from the earth-moon system and go into such an orbit. Hence many particles retain enough energy after escaping from the moon to avoid falling on or orbiting around the earth.

The escape is only temporary, however. The heliocentric orbit of these particles is practically the same as the orbit of the earth, and over a fairly long period—of the order of 100 million years according to Ernst J. Öpik of the Armagh Observatory in Northern Ireland—the earth probably sweeps up as much as 50 per cent of the particles in such orbits.



ORIGIN OF TEKTITES in the impact of a meteorite on the moon is depicted. The path of the meteorite is colored. Debris is ejected in all directions at angles of more

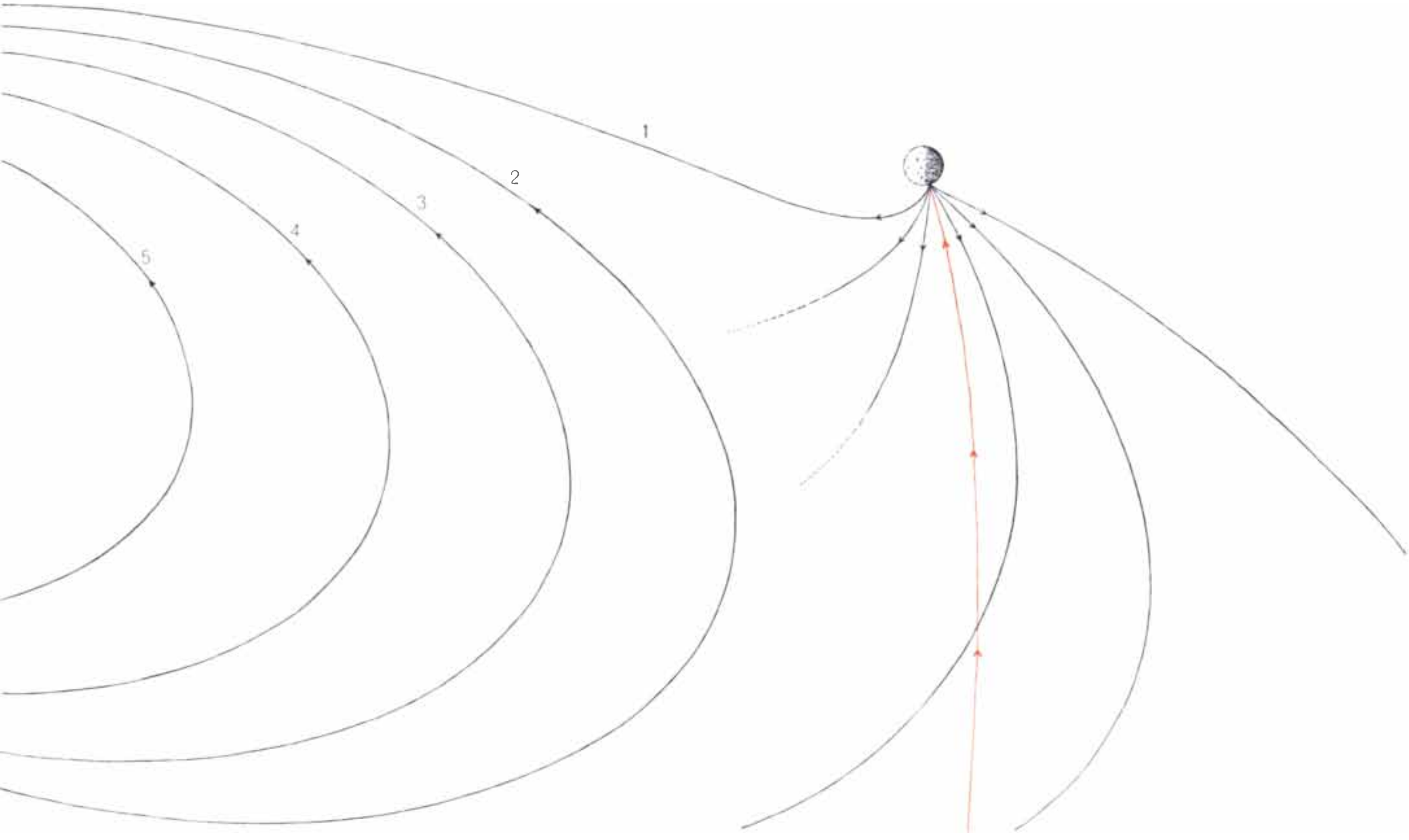
Of the material that leaves the moon but does not go into orbit around the sun, a small fraction comes directly to the earth and a larger portion is trapped in orbit around the earth. Recent preliminary calculations indicate that later, under the influence of the moon, somewhat less than 10 per cent of the debris in geocentric orbit comes to earth and the rest is diverted into heliocentric orbit. Öpik estimates that the lunar material that has reached the earth amounts to about a five-hundredth of all the meteoritic material that has fallen on it.

The geology of the strewn fields of tektites indicates that there have been only a few tektite falls in the past 30 million years; thus it is apparent that tektites make up only a small fraction of the lunar debris reaching the earth. The question of why no other samples of rock from the moon have ever been recovered and recognized is a most important one and rather difficult to answer. I shall discuss it after presenting in broad outline the evidence in favor of a lunar origin for tektites.

The claim that tektites are some sort of impact debris rests in part on the fact that some of them contain tiny spherules consisting of iron and up to 10.2 per cent nickel (in the form of the mineral kamacite) that resemble spherules found in rock ejected from known meteorite craters on the earth. Among natural minerals, as far as is known, the nickel-iron combination is unique to meteorites. The effective discoverer of the tektite spherules, E. C. T. Chao of the U.S. Geological Survey, reports that they, like the spherules from terrestrial impact areas, are covered with a network of pink crystals of the mineral schreibersite, which contains 13 to 15 per cent nickel. Chao has also identified in the tektite spherules the mineral troilite. This combination of minerals—kamacite, schreibersite and troilite—occurs only in meteorites and their impact debris.

A second important discovery, made by Elizabeth Viste and Edward Anders, then at the Enrico Fermi Institute at the University of Chicago, is that tektites do not contain the radioactive isotope aluminum 26, which results from long bombardment of a meteorite in space by primary cosmic rays. The absence of this isotope makes it clear that in their present form tektites have come only a short distance through space. Anders believes that they have been in space for 10,000 years or less. According to Öpik, a body would need several hundreds of millions of years to work its way to the earth from another planet or from the asteroid belt between the orbits of Mars and Jupiter. These findings by Chao and Anders are consistent with both a terrestrial and a lunar origin for tektites.

The study of one form of tektite found in Australia, the so-called australite button, has helped greatly in localizing the moon as the source of tektites. Dean R. Chapman of the Ames Center has recreated the buttons with remarkable verisimilitude by ablating, or eroding, spheres of glass of a similar chemical composition with heated gases in a wind tunnel. He has reproduced not only the flange of the button, which represents glass melted and rolled back from the tektite's front face, but also the system of circular or spiral ridges on the front face, the detailed shape of the striae within the flanges and even the accordion-shaped folds of the striae [*see bottom illustration on page 56*]. On the evidence of experiments it is hardly possible to doubt that australite buttons were given



than 45 degrees. Some of it goes into orbit around the sun; some falls to the earth. Here one large chunk goes into orbit around the earth. Its elliptical orbit decays almost to a circle as a result of slowing during repeated passages through the earth's atmosphere. At end of its fifth orbit it breaks into three pieces (*6a, 6b and 6c*), which are parent bodies of tektites. Each piece has a different orbit and therefore a different speed. The sequence of events in this hypothetical case is continued in the illustration on pages 54 and 55.

VARIOUS TEKTITES, dusted with white powder to bring out the modeling of their surfaces, are in the collection of the Smithsonian Institution in Washington. They were found ("*a*" *and* "*b*") on the island of Billiton, between Sumatra and Borneo, (*c*) in the Philippines, (*d*) on Martha's Vineyard off the coast of Massachusetts (this fragment is the only tektite ever found there) and (*e*) in Indochina. At bottom (*f*) are front (*above*) and back views of the same dumbbell-shaped Australian tektite, exhibiting respectively several ablation rings and a pronounced flange. The powder conceals the black color and glassy sheen of the tektites.

their final form while traveling at high speed through the atmosphere.

The amount and kind of ablation observed in the buttons indicate, according to calculations by Chapman and Howard K. Larson of the Ames Center and by Ernst W. Adams and Robert M. Huffaker of the NASA George C. Marshall Space Flight Center in Huntsville, Ala., that the buttons entered the earth's atmosphere at velocities ranging from 6.5 to 11 kilometers per second. Recently Adams reported new calculations based on precise measurements at the Goddard Center of the vapor pressure of molten tektites. The vapor pressure is lower than some authorities predicted; that is, an unexpectedly large number of molecules boil out of the tektite material. The effect of this phenomenon in a tektite passing through the atmosphere is to insulate the stone from friction with the air. The net result is paradoxical: low vapor pressure necessitates a higher velocity for a given amount of ablation than high vapor pressure. Adams' calculations indicate that the australites would have had to travel faster than seven kilometers per second to be ablated as much as they have been. This strongly suggests that tektites are not of terrestrial origin. If the Australian tektites had come originally from the single point on the ground represented by an impact, and if they had traveled at seven kilometers per second, they would have been strewn over a much wider area than they are.

The idea that tektites did not originate on earth is reinforced by a consideration of the angles at which these bodies could have entered or reentered the atmosphere. For a given amount of ablation the possible entry velocities can be correlated with the possible entry angles in curves plotted on a diagram [*see bottom illustration on page 57*]. Such a diagram shows that velocities less than 11 kilometers per second will give rise to tektite ablation only if the entry angles are rather shallow. Experiments in making craters demonstrate, however, that the bulk of material ejected from the crater follows trajectories with angles to the horizontal greater than 45 degrees (and, of course, falls back at the same angle), regardless of the angle of impact of the original object. A low angle is just what would be expected for entry from an orbit around the earth.

The possibility that tektites originated in the region of the asteroid belt, which is largely ruled out by Anders' observation on aluminum 26, requires velocities greater than 11 kilometers per second:

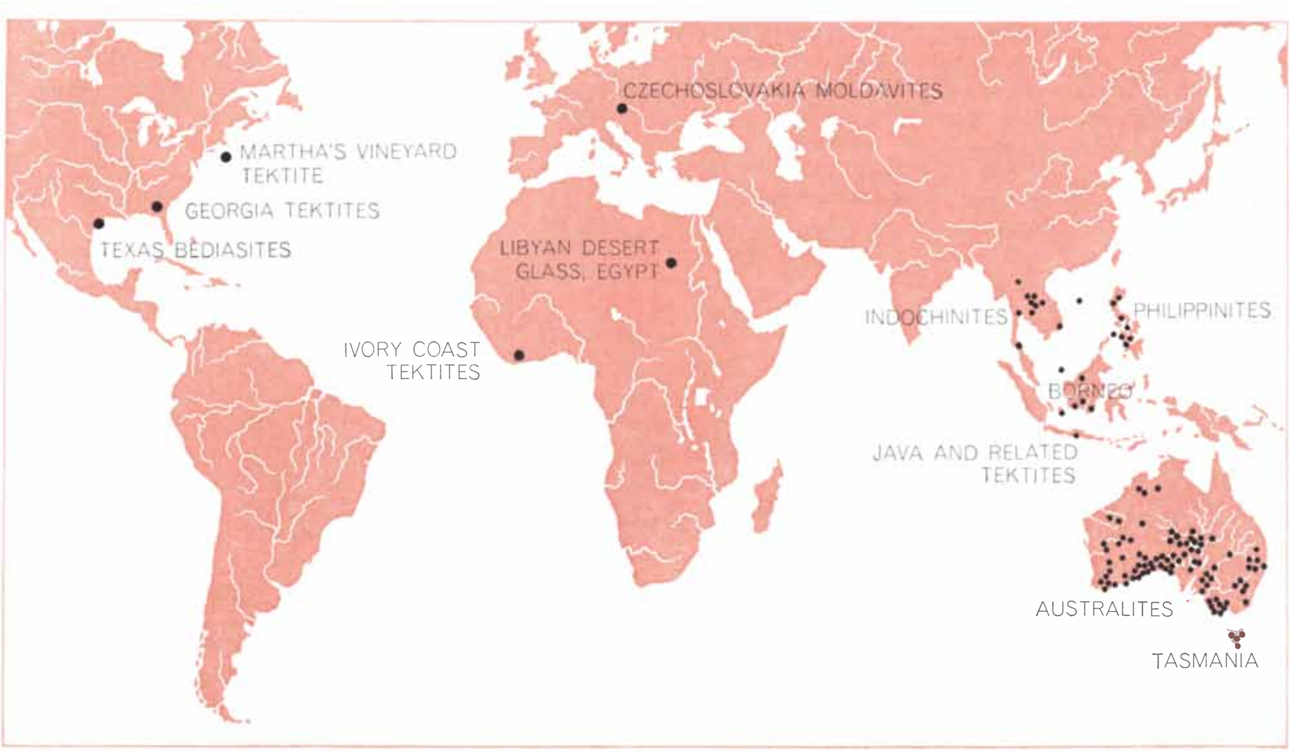
typically 17 kilometers per second, which is far too fast for the amount of ablation observed in australite buttons. Chapman's study of the ring-shaped waves on the face of the buttons also suggests an upper limit to the velocity near 11 kilometers per second, and corrections to Chapman's theory would tend to reduce this limit even further.

One of the most difficult problems facing the proponents of the terrestrial origin of tektites is explaining how the stones managed to get very far off the ground in the first place. As Harold C. Urey of the University of California at La Jolla and I have both pointed out, if tektites originated on the earth, to reach the limits of a strewn field they had to be boosted to a height of 50 kilometers or more and to arrive at this height with a velocity of at least four kilometers per second. The special boost is needed because a body moving upward at hypersonic speeds through the atmosphere will be stopped as soon as it has encountered a total mass of air approximately equal to its own mass. Typical tektites weigh less than 100 grams and are one or two centimeters in diameter. Since the whole atmospheric column weighs about 1,000 grams per square centimeter, individual tektites cannot force their way up through more than a few thousandths of the atmosphere—far less than one kilometer. The only mechanism that might lift them to a height of 50 kilometers and give them the necessary velocity would be the blast wave from a tremendous explosion on the ground.

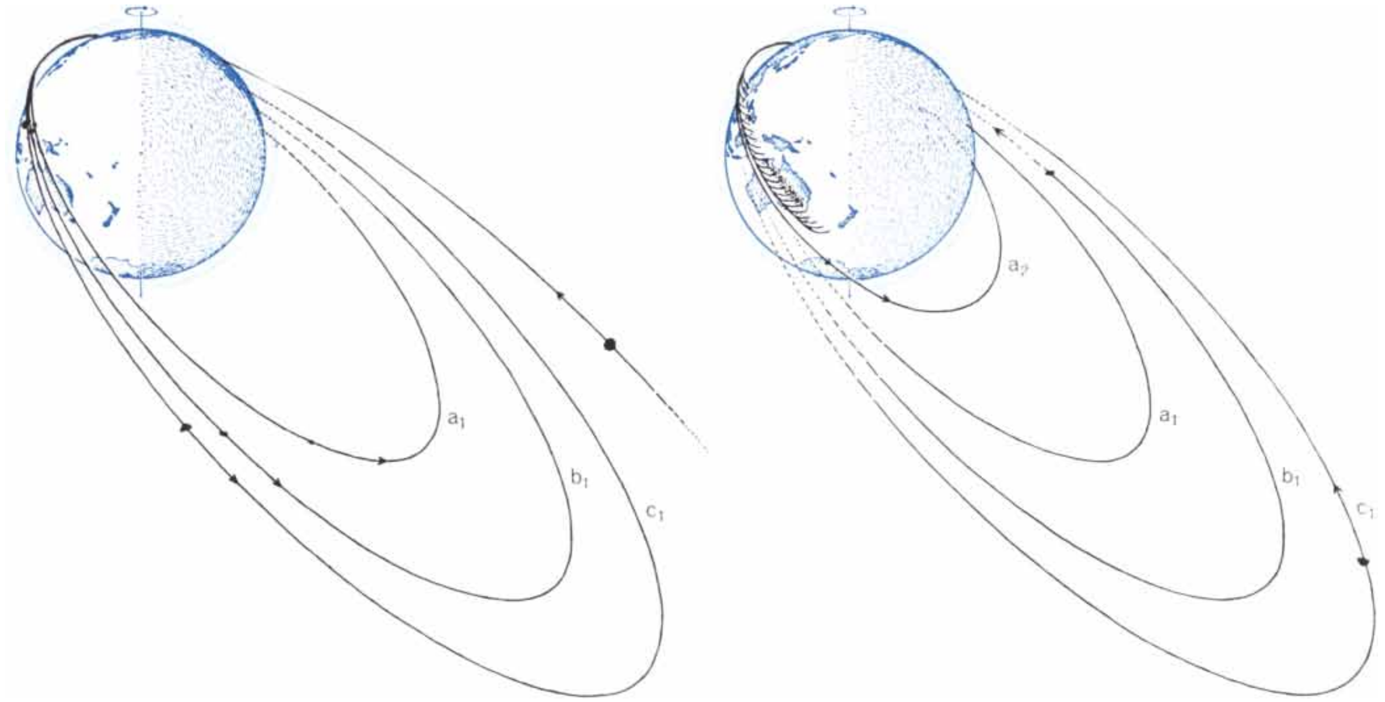
It is true that the impact of a large meteorite would produce a blast wave. The theory of blast waves has been developed during recent years as a result of interest in nuclear explosions; the Atomic Energy Commission has prepared tables and even a slide rule for calculating the effects of blasts up to 20 megatons, which is equivalent to about 10^{24} ergs. Extrapolations from this figure by accepted scaling laws show that an energy of several times 10^{28} ergs must be applied to the atmosphere to produce a blast wave capable of lifting tektites to a height of 50 kilometers. The extrapolation is, of course, somewhat risky, but it appears that one is likely to underestimate the energy required rather than to overestimate it, because blast waves dissipate quickly at high altitude and therefore require more energy to sustain them. A meteorite capable of generating 5×10^{28} ergs would have created on the earth a crater as large as the lunar crater Copernicus, which is about 90 kilometers in diameter. The tektites of the Far East are some 600,000 years old, yet there is no evidence of a large crater that young in the Far East or anywhere else on the earth. Geological processes could not have obliterated such a structure, if it had existed, in so short a time.

Another point in many ways difficult to reconcile with such blast waves is that tektites appear to have been shaped in a remarkably peaceful environment. Many of them resemble liquid drops; they have been molded into spheres, oblate spheroids and "teardrops." Ordinarily such forms are produced by the forces of surface tension. Even more striking evidence of surface tension are the large vesicles or bubbles found inside tektites. Hence the forces that shape tektites are the same as those that form a soap bubble. The tektite forces are somewhat stronger, since the surface tension of liquid stone is several times greater than that of water, but they are of the same order of magnitude. As Chapman has remarked, one of the large Asiatic tektites would be so delicate in the liquid state that a breath could destroy it.

An idea of the pressures that exist in an impact, even one far too weak to produce a Copernicus, can be obtained from the recent discovery by Chao and Shoemaker of the minerals coesite and stishovite in the glass from Meteor Crater in Arizona and other impact craters. Solid quartz is compressed by 25 per cent to produce coesite and by 50 per cent to make stishovite. A considerable distance



LOCATIONS OF TEKTITES are shown on world map. The author believes that the various groups in the Far East are actually a single "strewn field." Some investigators count them as five or six strewn fields. The moldavites are beautiful light green translucent stones.



EVENTS NEAR THE EARTH that produce tektites begin, according to author's theory, when a large object from the moon breaks into several parts in atmosphere (*left*). The piece with the shortest orbit (*a*) travels fastest and that with the longest orbit (*c*) slowest.

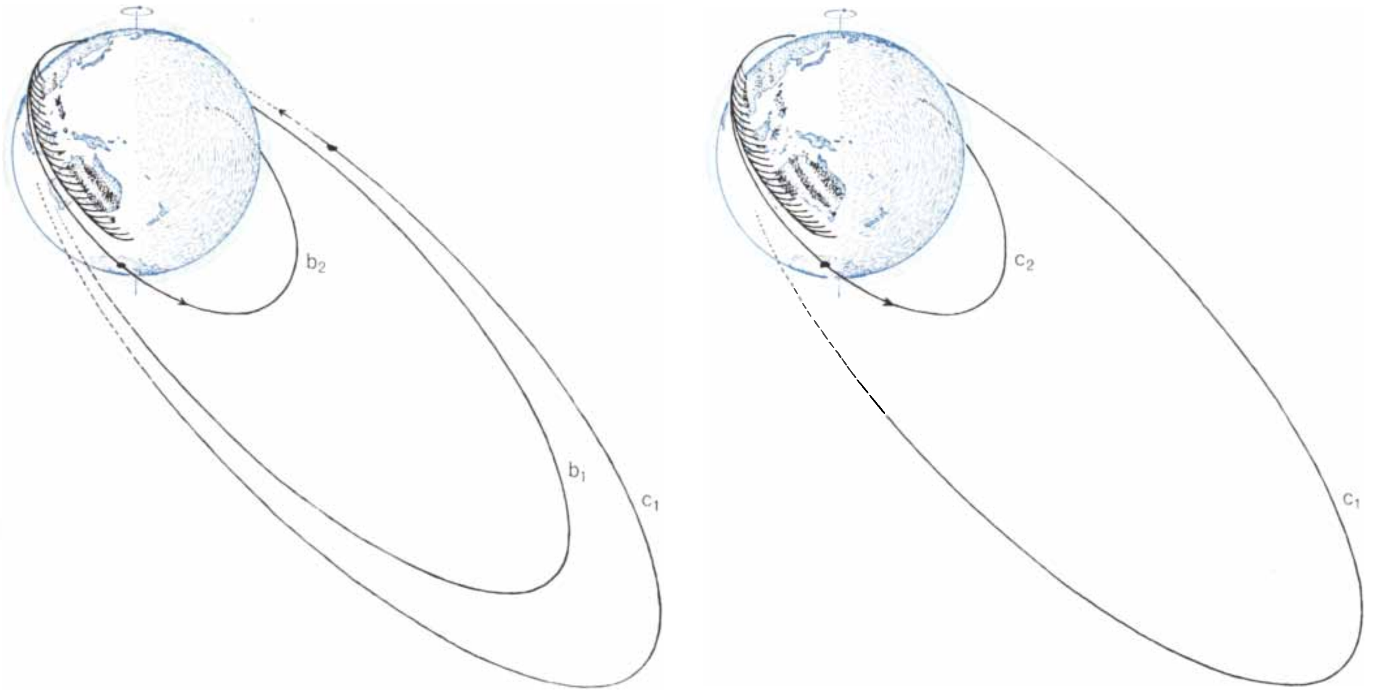
from the center of impact of these craters tough, hard stones were smashed, ground, partly melted and mixed in a confusion unmatched in other types of geological deposit. Of all the unpromising environments for the production of such delicate structures as tektites, a massive impact on the earth would seem to be the worst.

On the evidence presented by tektites themselves, it is therefore not difficult to eliminate the earth and any part of the solar system much beyond the moon as their point of origin. It is, perhaps, more difficult to determine exactly how they made the trip from the moon to the surface of the earth in such a way as to acquire the forms they display today. A possible clue to this problem is presented by the remarkable meteor shower of February 9, 1913, for which I have proposed the name Cyrillids. (February 9 is the feast day of St. Cyril of Alexandria.) The bodies of this shower appear to have been a group of small natural satellites of the earth, an interpretation first put forward in 1913 by C. A. Chant of the University of Toronto. His hypothesis has been supported by observations later brought to light by other investigators.

The Cyrillids are thought to have been natural satellites of the earth largely because the meteors traveled almost parallel to the ground over an arc of nearly 90 degrees from Saskatchewan to a point off the coast of Brazil [*see top illustration on page* 57]. The delay in the arrival of the noise from them—a roar like a train—and other evidence indicate that their altitude was about 80 kilometers. The observations, like nearly all meteor observations, came from amateurs, but several considerations make their report unusually reliable. In the first place, Jean Kovalevsky of the Bureau des Longitudes in Paris has shown that, although most people cannot be relied on to give the azimuth or altitude of meteors, they usually answer correctly such questions as whether a meteor came from the left down to the right. In the case of the Cyrillids, the public from one end of the line to the other insisted that the bodies were in level flight. The second point is that these objects traveled with, to use Chant's phrase, "majestic slowness," in the now familiar manner of artificial satellites. This gave the public a good look at them. Furthermore, the last members of the shower crossed the sky some minutes after the first, so that perhaps many people had recovered from their initial surprise and took a better second look. Finally, a careful study of where reports of the flight were and were not made provides a consistent picture of the path of the Cyrillids. Altogether it is difficult not to conclude that they were a group of natural satellites.

It seems to me highly probable that they were from the moon. Such material is detached hourly by meteorite impact, and if its velocity falls within certain fairly broad limits, it automatically goes into orbit around the earth. Barbara E. Shute of the Goddard Center has shown that the moon and the sun would perturb a certain proportion of bodies in orbit around the earth, causing them to encounter the atmosphere and begin to slow down. Then the elliptical shape of the orbit would decay, finally becoming nearly circular. If material in the form of liquid drops could be detached from objects such as the Cyrillids, it would produce tektites. (The Cyrillids themselves, as far as is known, left no tektites.)

Adams and Huffaker have shown that if the objects are large enough, a moderately thick surface layer will melt and fall off in the form of liquid drops. Their argument takes account of the fact that the thermal conductivity—the velocity of the flow of heat—of tektite glass is very low. The viscosity of the material, however, is quite high. The low thermal conductivity means that when the surface of a tektite is very hot, the temperature gradient between the outside and the inside of the object is quite steep: at the surface the material is being vaporized and only a short distance below the surface it is still solid. The layer of liquid between the vapor and the solid is so



On its second orbit chunk *a* spreads tektites in a relatively narrow path across Far East and then plunges into the ocean. Chunks *b* and *c* follow later, on their second orbits, as the earth turns below them. This accounts for the width of the Far Eastern strewn field.

thin that viscosity can effectively prevent the liquid layer from being dragged off by aerodynamic forces. Öpik has pointed out that liquid flow is neither expected nor usually found in stony meteorites. This is why most tektites show no evidence of flow after solidification. In the exceptional case of the australite buttons a small amount of flow occurred because of their nearly horizontal flight, which led to a long trip through the atmosphere and prolonged heating.

Although liquid flow normally does not occur when heat diffuses through the stone by conduction alone, the situation is different in the case of an object—perhaps a parent body of tektites—that is considerably larger than typical meteorites and tektites. Such a body would penetrate to a considerable depth in the atmosphere before aerodynamic forces could arrest it. Consequently a very strong shock wave would form ahead of it and a thin layer of air in the shock region would be accelerated suddenly from zero velocity to a velocity like that of the body itself. In the shock layer the temperature would rise to some thousands of degrees, radiating a large amount of heat compared with the heat being conducted away. This radiant heat would fall on the large body and, if the body were partially transparent—like some natural glasses—it would penetrate much deeper than the heat transported by conduction. Adams and Huffaker have calculated that on the surfaces of a large body the process would form a liquid layer thick enough to shed drops that would solidify into tektites.

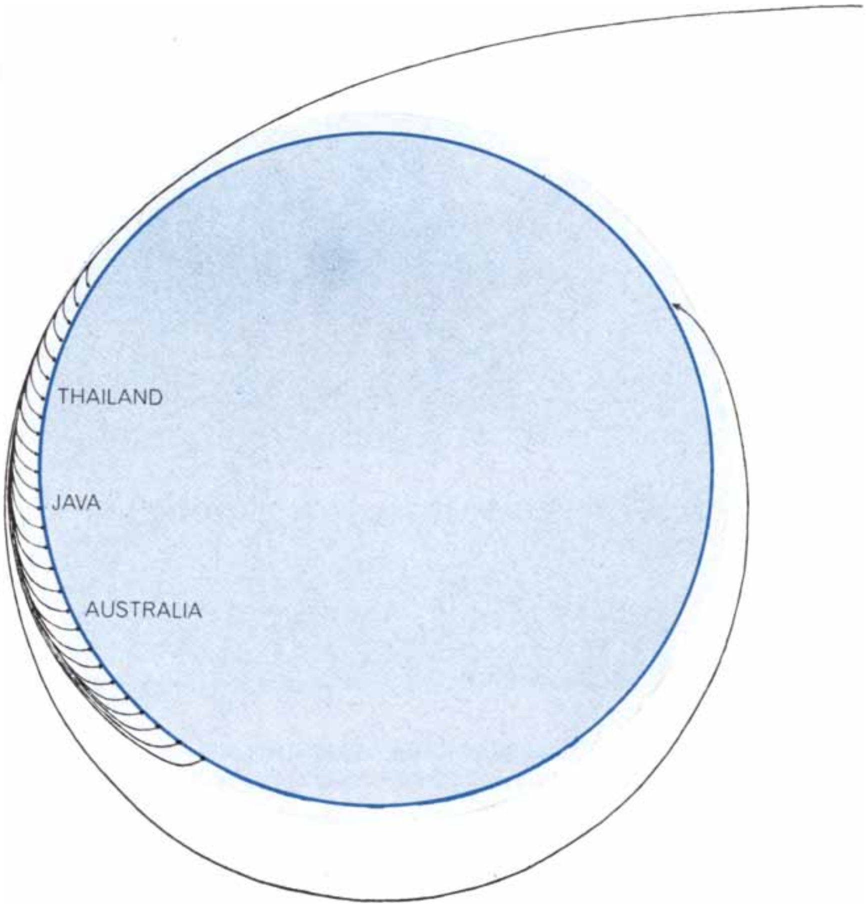
This theory of tektite formation has the beauty of explaining why tektite strewn fields are so rare. Large impact ejecta from the moon are rare, and the required grazing encounter with the earth's atmosphere, as opposed to a plunge almost straight down into it, is also rare. The coincidence of these two factors might reasonably be expected to occur only once in some 15 million years. The theory also accounts for the fact that tektites are found in strewn fields and not all over the earth; they come from stony bodies that travel over only a limited arc of the earth's surface.

The theory of Adams and Huffaker also allows an escape from the difficult paradox presented by the presence of both metallic spherules and large bubble cavities within tektites. The violent events suggested by the spherules occurred at the surface of the moon, whereas the bubbles appeared days, months or years later high in the atmosphere of the earth. Chao has shown, incidentally, that it is possible to melt and reshape tektites that contain nickel-iron spherules without any obvious change in the spherules. Thus the spherules would not be damaged during the melting of the stone that occurs near the earth.

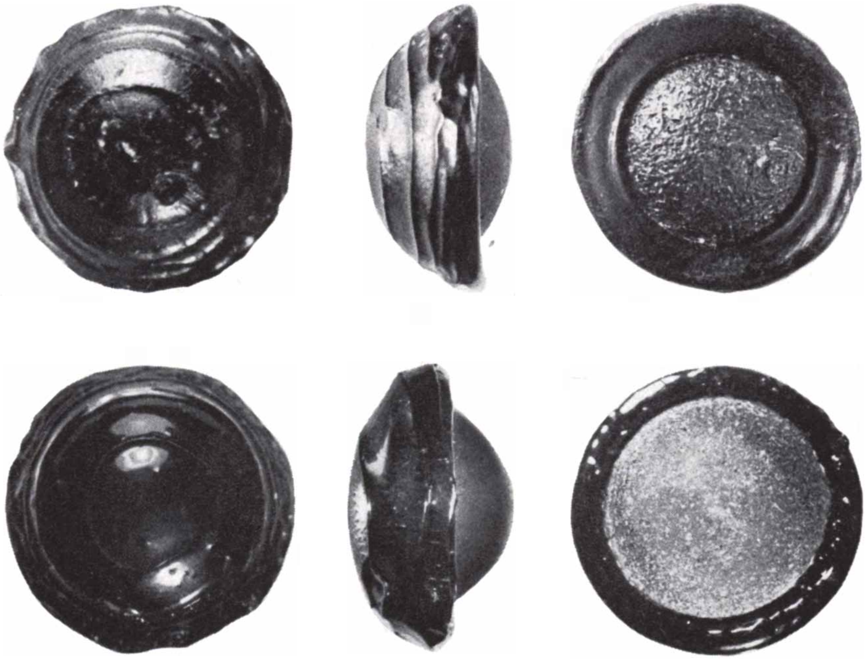
As a result of all these discoveries, I find no reason to regard tektites as being enigmatic. To me they are bodies with a fairly clear history. It begins with impact on the moon. The next major event is entry into the earth's atmosphere and a shaping into droplike forms, as well as the appearance of cavities. In the later stages of flight near the surface of the earth comprehensible shapes appear, at least in the case of the australite buttons. The marks and grooves on other tektites will, I believe, be explained someday as resulting from ablation under conditions of transition and turbulence in the atmosphere.

It is perhaps needless to say that this theory of tektite origin has its critics. Urey, for example, believes that the stony meteorites called chondrites, but not tektites, are the result of impacts on the moon. He points out that the grazing encounter with the atmosphere proposed by Adams and Huffaker can account for only a tiny fraction of debris from the moon and asks what becomes of the rest. Although an answer is not easy to give, some well-based speculation is possible.

For one thing, the chemistry of tektites is almost exactly like that of granite, even to trace elements. Only the volatile oxides (such as water, soda and potash) found in granite are partly or wholly missing from tektites. If tektites are truly from the moon, other bits of lunar



PATH OF PARENT BODY and of tektites is shown in cross section. Heating occurs in atmosphere (*shading around earth*) and tektites (*short arrows*) drop off. Some tektites form just as the parent body leaves the atmosphere and these solidify outside the atmosphere before plunging to earth. They are ablated on the trip down. Parent body falls into the sea.



TEKTITE ABLATION and excellent imitation of it are shown in these photographs from the laboratory of Dean R. Chapman of the Ames Research Center at Moffett Field, Calif. Front, side and back views of an australite button tektite are seen in the top row. Similar views of an artificial tektite produced by Chapman in wind tunnel are shown in bottom row.

debris of the same composition but different in appearance might easily go unrecognized. Perhaps they are among the slaggy objects so often offered to museums as meteorites and so swiftly rejected as not meeting the criteria for meteorites established from stones that have been accepted as meteorites. There is at least one case of an alleged fall, near Igast in Estonia, of a handful of stones with a chemistry like that of a tektite but of a very different structure. It is tantalizing to realize that, because of their chemistry, prototektites probably survive much longer than ordinary meteorites and indeed may be so common that most people have at one time or another set eyes on one.

Among the tiny meteorites called micrometeorites there is a class of glassy spherules about which little is known but which are probably not related to the stony meteorites. Richard Schmidt of the University of Wisconsin has recently shown that these objects have indexes of refraction and densities in the range of those found in tektites. Preliminary chemical analysis of one of them, Schmidt reports, reveals a close resemblance to tektites. Adams and Huffaker have suggested that if chunks of debris from impacts on the moon enter the atmosphere at a steep angle rather than a grazing one, they might break up completely into such micrometeorites.

Chapman objects to the idea of tektites as ablation droplets. He believes that tektites were formed on the moon and arrived directly therefrom rather than by way of a decaying satellite orbit. He points out that his experimental studies of tektite ablation indicate that for a decaying satellite orbit, with velocities as low as eight kilometers per second, no ring-shaped waves should appear on the surface of tektites. On the other hand, Simon Ostrach of the Case Institute of Technology believes that such waves might appear even at lower velocities, as a result of deceleration.

Chapman also believes that the extreme fragility of the larger tektites, when they were liquid, indicates that they were subjected to such low air drag, if any, that melting could not have taken place through aerodynamic heating. Here, since the discrepancy is a matter of a factor of two or so and arises only in the case of large tektites, one could suppose that the drop was detached just as the parent body left the atmosphere on one of its orbits, and owed its preservation to viscosity and to the opportunity to cool outside the atmosphere while surface tension shaped it.

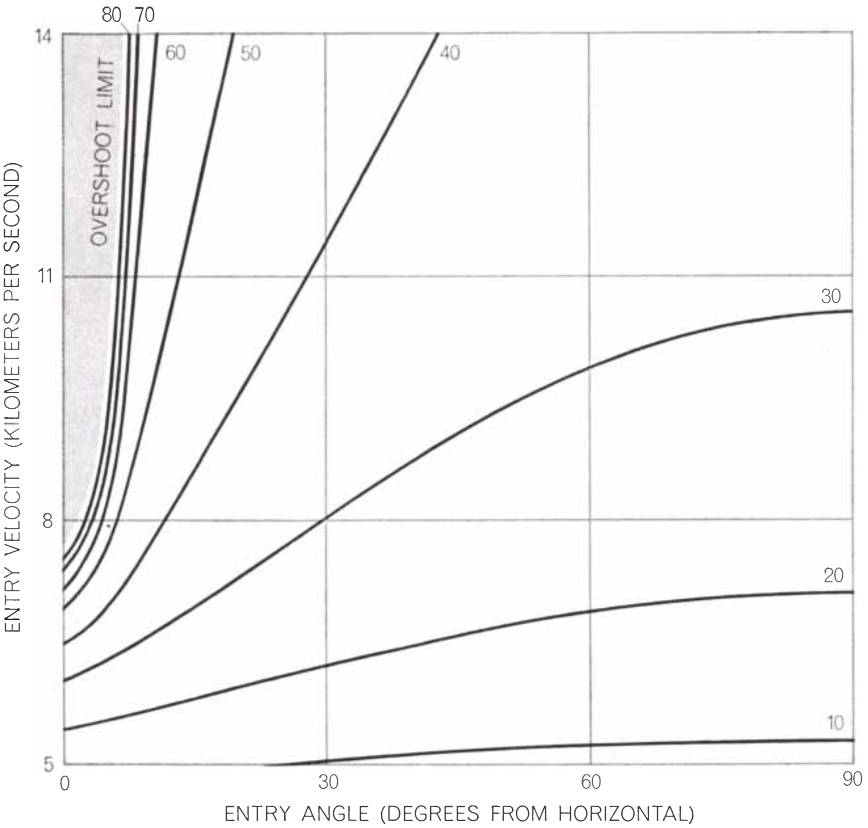
As Urey has pointed out, Chapman's theory would mean that other tektites formed on the moon would go into orbit around the sun to be captured later by the earth. These should be found all over the world rather than in strewn fields, and they should contain aluminum 26. Chapman has some difficulty with this, but he has suggested that cosmic rays, direct radiation from the sun and other conditions in space might have changed such tektites from glass into crystalline rock, which would destroy their unique appearance and cause geologists to overlook them.

Regardless of the differences among the proponents of lunar origin, it seems to me that the aerodynamic and other evidence clearly indicates that the moon is the source of tektites. I shall therefore conclude by examining some of the fascinating consequences this has for theories of the origin and subsequent history of the moon.

If crystallized, tektites would have a density of about 2.8 grams per cubic centimeter, whereas the moon as a whole would, at zero pressure and low temperature, have a density of 3.4. The crust and mantle of the earth, under the same conditions, would have respective densities of 2.8 and 3.3. This suggests that the moon, like the earth, is able to produce a thin outer crust less dense than its interior. In that case the moon once had a hot interior, since the only process by which a low-density crust could be formed on the moon appears to be by the separation of materials in a fluid magma. Radioactive dating indicates that tektite material was differentiated from the primary magma during the past 500 million years, and if the moon's interior were that hot 500 million years ago, it still has not had time to cool. The idea is supported, incidentally, by observations in the U.S.S.R. in 1961 and just recently at two U.S. observatories of what appears to be the emission of gas on the moon [see "Science and the Citizen," page 67].

The chemical resemblance, or near identity, between tektites and common earth materials, which is far closer than the resemblance between either and any accepted meteorites, would strongly indicate that the moon is derived from the same original materials as the earth. Therefore either the moon formed alongside the earth or broke away from it. I find it difficult to see any other way to account for the moon on the basis of the theory I have presented here of the origin of tektites.

OBSERVATIONS OF CYRILLIDS (*black dots*), a meteor shower seen in 1913, reveal their path. The second pass, or orbit, was not observed and is hypothetical. Such objects, traveling nearly parallel to the earth's surface, may be the parent bodies of tektites.



ENTRY VELOCITIES AND ANGLES for given amounts of ablation are plotted. Figure at end of each curve is per cent of ablation. A typical australite button is 75 per cent ablated. Thus at the speeds shown here it could not have come in at an angle to the horizontal greater than 10 degrees or so. The diagram is based on studies conducted by Ernst W. Adams and Robert M. Huffaker when both were at the Marshall Space Flight Center in Huntsville, Ala.

HOW CELLS ATTACK ANTIGENS

An army of defensive cells protects the body against invasion by foreign substances: the antigens. The specialized functions of these various "inflammatory" cells are now being clarified

by Robert S. Speirs

All organisms resist the violation of their internal integrity by foreign substances. The higher animals are protected against such invasion by several defenses. Their skin serves as a first-line barrier, and within the body connective-tissue fibers and certain organs (notably the spleen and lymph nodes) act as filters that tend to trap foreign material and prevent it from being spread into other tissues by the body fluids. These passive defenses are incomplete and rather easily breached. The body's main reliance against antigens, or alien invaders, is the army of cells that destroys or neutralizes the antigens in what is known as the immune reaction.

This phenomenon is most easily observed when tissues are invaded by bacteria through a cut in the skin. We then witness a dramatic series of events called the inflammatory response. Teams of "inflammatory" cells mobilized by the body rush to the site and begin to destroy or inactivate the bacteria in a systematic way. Evidently the bacteria are in some manner recognized as foreign. Some of the defending cells engulf them and proceed to break them down by means of digestive enzymes. Many of these cells are in turn destroyed by toxins released by the bacteria. The area becomes a battleground strewn with swollen and broken cells, debris and fluid. If the body has previously been invaded by the same kind of bacterium, the inflammatory reaction is quicker and more violent. Normally the defending cells overwhelm the bacteria; scar tissue then begins to form and knit together the healing tissues.

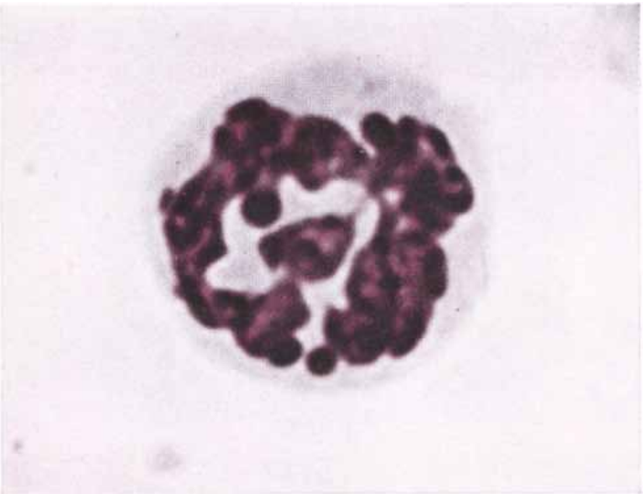
We know that the inflammatory cells are produced by the bone marrow, the thymus gland and the lymphatic system; that some of them, called plasma cells, synthesize the substances known as antibodies, and that the antibodies can react with and neutralize antigens. In the case of bacteria the antibodies generally take effect by covering the bacteria with a coat that makes it easier for the inflammatory cells to engulf and destroy them [see "White Blood Cells *v.* Bacteria," by W. Barry Wood, Jr.; SCIENTIFIC AMERICAN, February, 1951]. Through studies carried on in laboratories all over the world, much has been learned about the immune reaction. Sir Macfarlane Burnet has discussed the progress of this investigation in several articles in *Scientific American* [see "How Antibodies Are Made," November, 1954, "The Mechanism of Immunity," January, 1961, and "The Thymus Gland," November, 1962]. It is becoming possible to see precisely what questions must be answered if we are to arrive at a clear understanding of the mechanism of immunity.

How do the inflammatory cells identify a foreign material as alien? Exactly how do they attack it? How do the cells "remember" the chemical composition of an antigen so that when it appears a second time they immediately begin to produce the right kind of antibody to neutralize it?

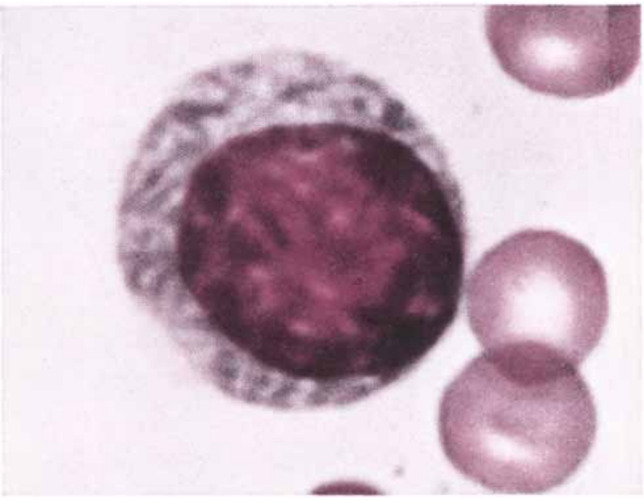
If we knew the answers to these questions in full detail, a number of important medical problems might be solved. The immune reaction is not always beneficent; for example, it interferes with the grafting of tissues or organs from one person to another. If the immune response could be reliably suppressed, it would be far easier to replace defective organs. Similarly, diseases caused by abnormal immune reactions might be prevented or cured. Specific antibodies for the various infections could be produced on a large scale by growing plasma cells in tanks. And the ability to manufacture antibodies in tissue culture would provide biochemists with an important tool for investigating the steps in the synthesis of proteins by cells.

In our laboratory at the Downstate Medical Center of the State University of New York College of Medicine we have been making a detailed study of the inflammatory response, with the object of learning something about the cells' production of antibody at the molecular level. To bring the problem within reasonable reach of analysis we selected a comparatively simple antigen—not a complex bacterium but the toxin secreted by a bacterium. The one we chose is tetanus toxin, the substance made by the bacterium *Clostridium tetani*. Before immunization became common, this antigen was the frequent cause of "lockjaw." The tetanus toxin is relatively easy to purify and detoxify (that is, to reduce to a "toxoid"), and extremely sensitive methods are available for detecting and measuring it. Moreover, it is a simple matter to make it radioactive by incorporating tritium (the radioactive isotope hydrogen 3) in the molecule so that we can trace what happens to the antigen after it is attacked by the inflammatory cells in the body. Its presence and location in cells can be detected by radioautography [see "Autobiographies of Cells," by Renato Baserga and Walter E. Kisieleski; SCIENTIFIC AMERICAN, August, 1963].

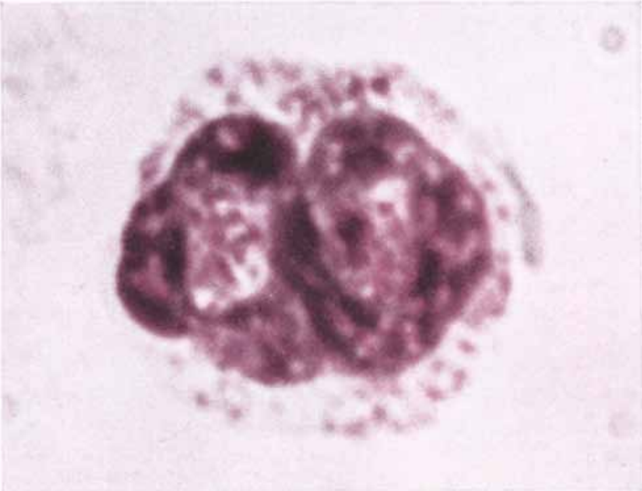
What happens when we first inject this antigen into a mouse? One of the earliest indications of the response is the arrival of the white blood cells known as neutrophils, which are characterized by fine granules in their cytoplasm (that part of the cell which lies between the nucleus and the outer membrane). Crawling by amoeboid movement, the neutrophils swarm into the area of the



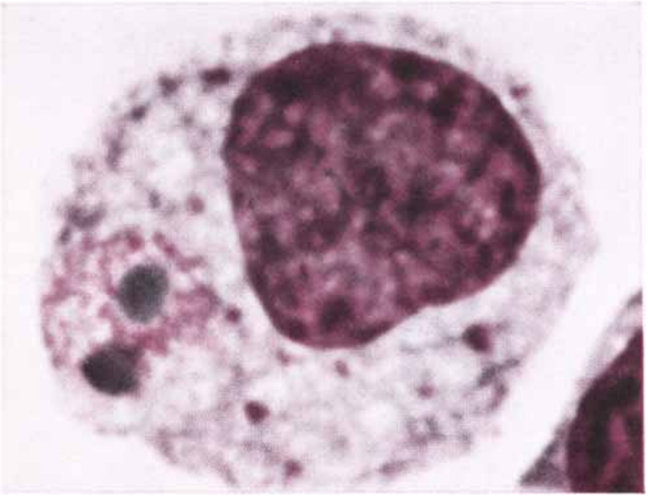
NEUTROPHIL is a white blood cell produced in bone marrow. The nucleus (*dark area*) is drawn out into segments; cytoplasm contains fine granules and enzymes that digest captured antigens.



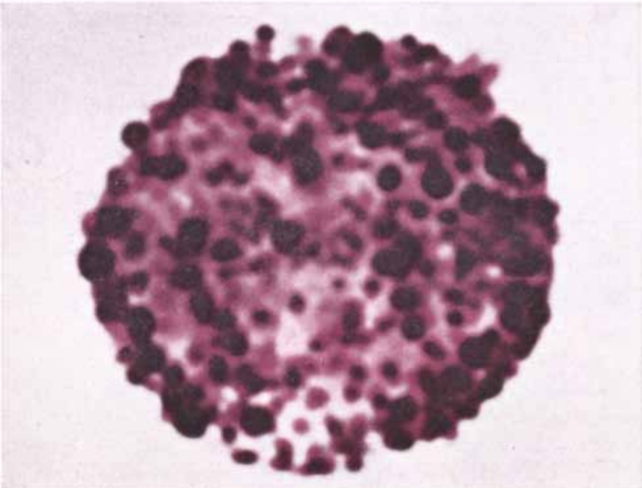
LYMPHOCYTE has a large, spherical nucleus and no granules in its cytoplasm. Lymphocytes are produced in the various lymphatic tissues. The smaller bodies at right are red blood cells.



EOSINOPHIL can be distinguished from a neutrophil by the larger granules in its cytoplasm; these granules are easily stained with the red dye eosin. Hence the name eosinophil, or "eosin-loving."

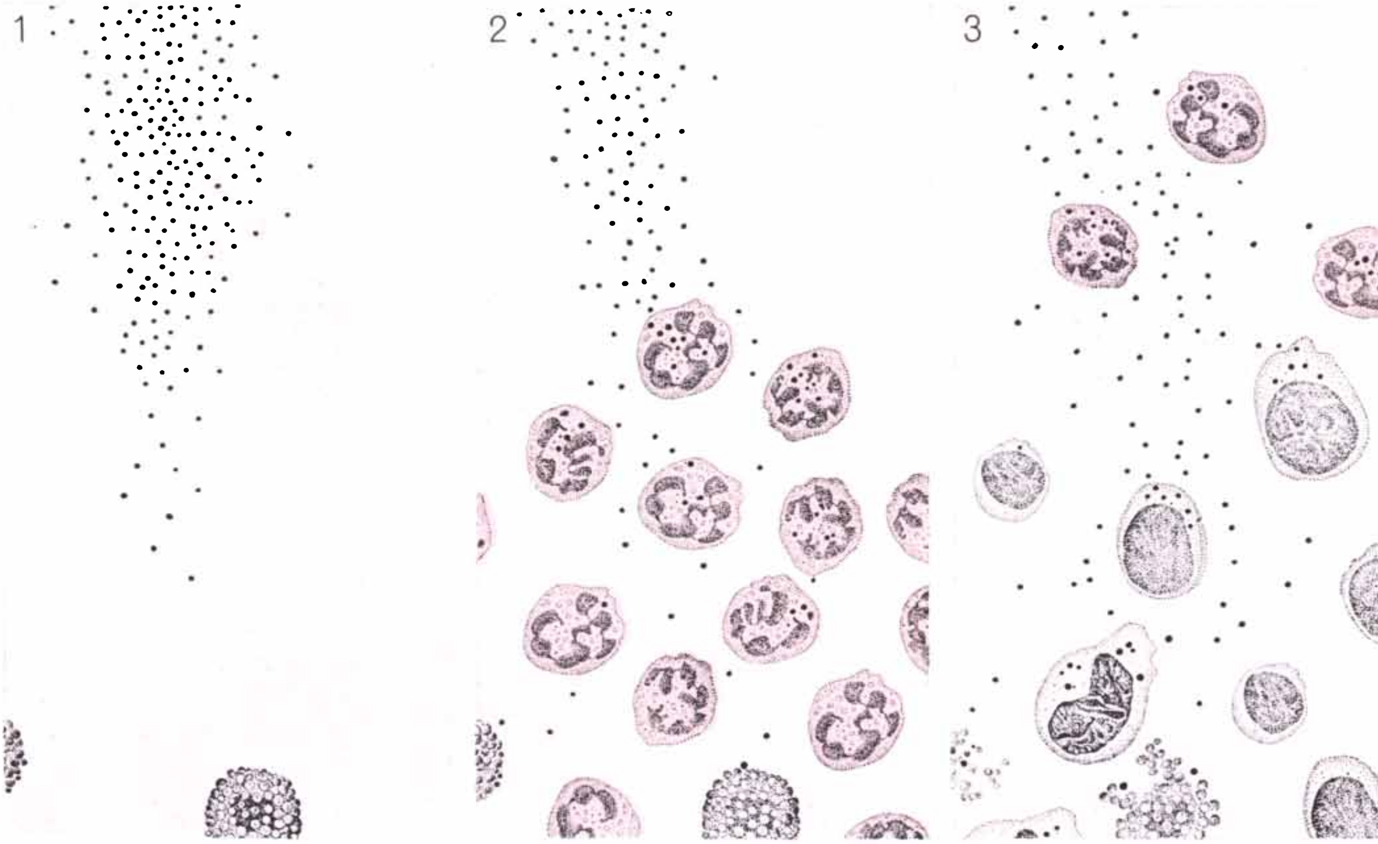


MACROPHAGE is formed when a lymphocyte or monocyte engulfs other cells and cell debris at the site of inflammation and swells to a large size. Engulfed cell at lower left is an eosinophil.



MAST CELL, or tissue basophil, contains very large granules, which store enzymes and other substances; these are released in the area of inflammation and intensify the response to the antigen.

PLASMA CELL is a morphological variation of a macrophage that produces and secretes antibody during the later stages of inflammation. All the photomicrographs in this article are of mouse cells.



PRIMARY RESPONSE of the inflammatory cells to an injection of antigen (*black dots*) into the body of a mouse that had not been exposed previously to this particular antigen is depicted in this series of drawings. Large-granuled mast cells normally at the site (*bottom of 1*) disintegrate on contact with the antigen (*bottom of 2*), releasing enzymes and other substances that intensify the inflammation. The first motile defensive cells to arrive at the site are the neutrophils (*2*), which begin to engulf the particles

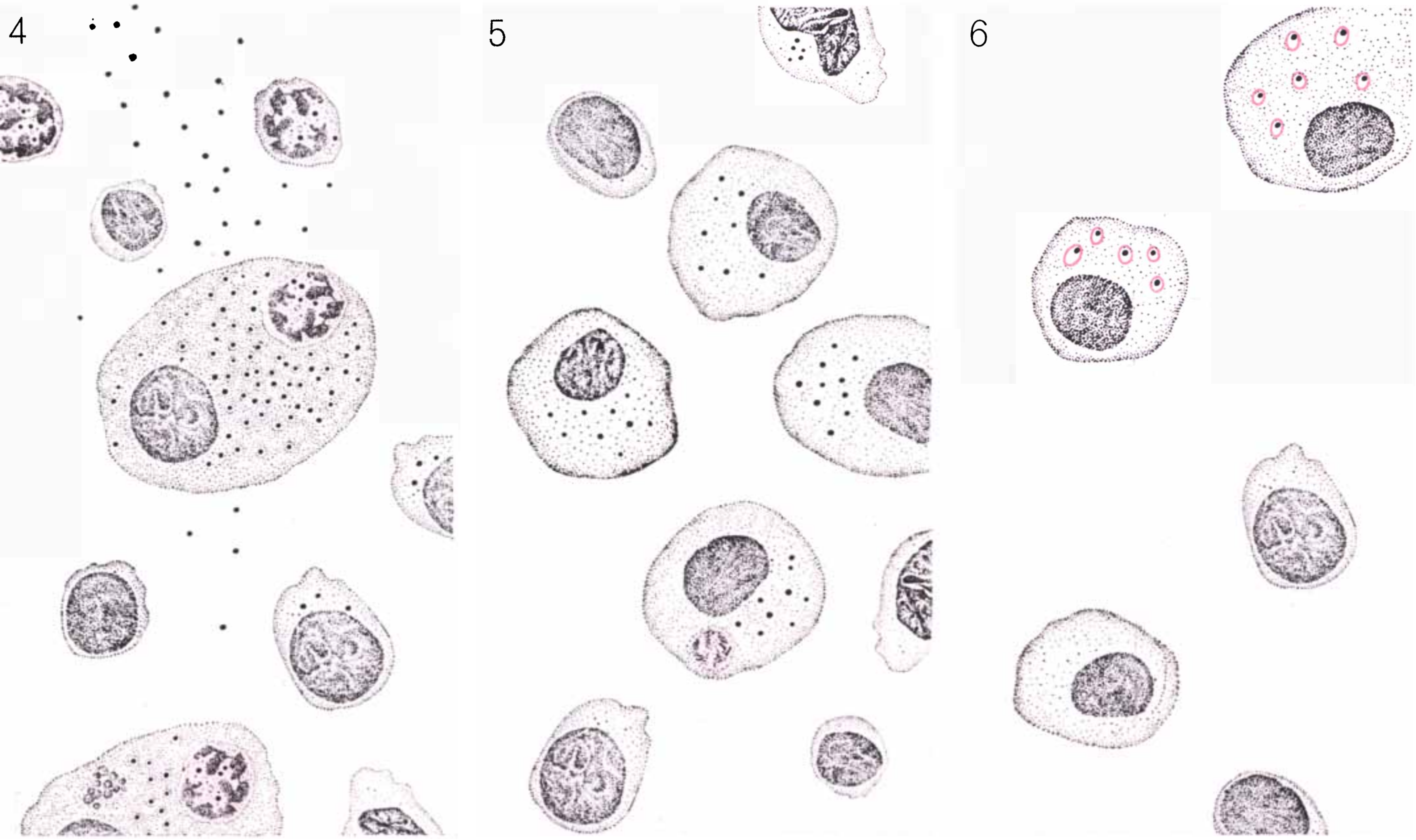
injected antigen from the blood vessels and the surrounding tissues. They begin to engulf the particles of antigen. The neutrophils contain a large supply of enzymes that are effective in digesting the antigen. It soon appears, however, that these cells are only an advance guard—an expendable emergency squad that prepares the way for the main attack. Within a few hours the neutrophils begin to break down and spew their contents into the fluid of the battle area. A second wave of slow-moving lymphocytes and monocytes moves into the area and proceeds to mop up the antigen and the disrupted neutrophils as well.

At first the lymphocytes and monocytes are fairly small, with little cytoplasm. Feeding on the debris in the inflamed area, they grow in size and become macrophages, swallowing up the antigen, the neutrophils and their contents and also granules and enzymes from mast cells, which apparently are disintegrated by the antigen. The degenerating mast cells release histamine, heparin, serotonin and other substances that intensify the inflammation. Meanwhile many of the macrophages synthesize deoxyribonucleic acid (DNA) and multiply by cell division, thus filling the inflamed area with an abundance of white cells.

The process goes on until the cells have disposed of all the antigen. They break most of it down, by means of enzymes, into amino acids and sugars, which then nourish the cells.

The studies with radioactively labeled antigen have brought to light the interesting fact that some component of the antigen evades destruction and remains within certain cells for months after the inflammation has subsided. It is carried away from the scene of battle by macrophages that migrate to the spleen, lymph nodes and other lymphatic tissues all over the body. There the radioactive material lingers long after the cells that engulfed it have died. Somehow it keeps its identity and is passed on from cell to cell as old cells die and new ones take it up. It seems that this surviving component of the original antigenic material is largely responsible for the vigor and effectiveness of the body's response to any later invasion by the same antigen.

In our experiments performed at intervals after the inflammation subsided the mice that had received the radioactive antigen were given a new injection of the same antigen, this time not labeled with tritium. To this second attack the pattern of response was somewhat different. Neutrophils again arrived at the site first, but not so many of them. Macrophages, on the other hand, turned up in considerably greater number. Many of these cells contained remnants of radioactive material derived from the first injection of antigen. They turned out to be hypersensitive to the newly injected antigen. Shortly after arriving at the area of the injection they began to swell and form large fluid vesicles within their cytoplasm. They became rigid and inactive and attracted large numbers of the cells known as eosinophils (so named because they are easily stained by the acidic red dye eosin). The eosinophils, which are found at the site of the primary response in much smaller numbers, attached themselves to the swollen cells and penetrated their interiors, causing them to become completely disrupted. Other macrophages and lymphocytes moving into the inflamed area then engulfed the fragments of broken cells and also the worn-out eosinophils.



of antigen. These are followed by a wave of slow-moving lymphocytes and monocytes (*3*), which proceed to engulf the antigen and the disintegrating neutrophils and mast cells as well (*4*). This process causes the lymphocytes to swell up and become macrophages, which eventually engulf all the free antigen in the area (*5*). Although most of the antigen is broken down by enzymes into amino acids and sugars, some is preserved within macrophages by combining with ribonucleic acid, or RNA (*colored circles in 6*).

The cellular response to the second invasion of antigen differed in another important respect from the primary response to the first invasion. Cell division among the macrophages began earlier. Many plasma cells were formed, and there was considerable production of antibody. The inflammatory response continued until all the antigen was either neutralized or destroyed.

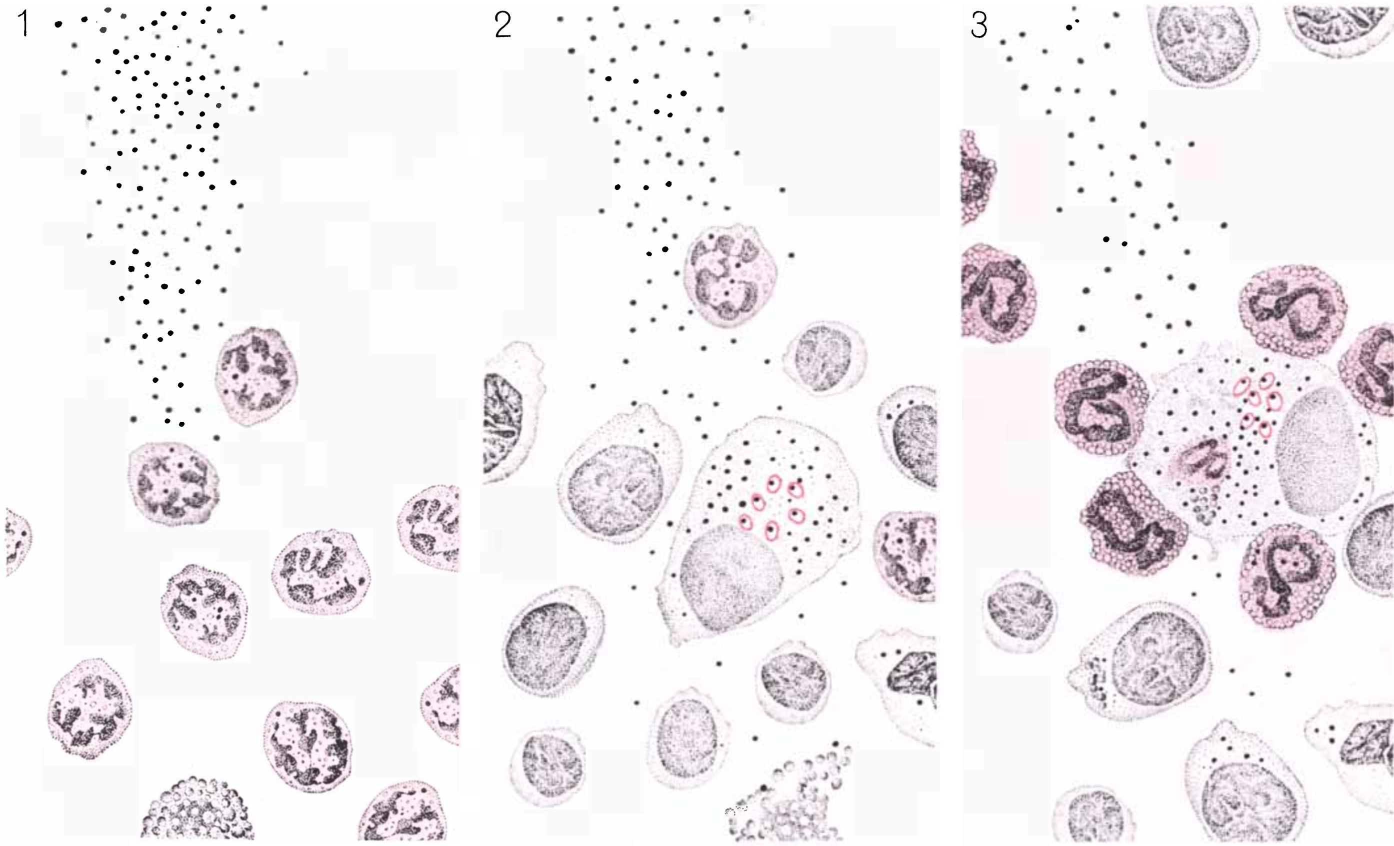
Surprisingly, it turned out that the plasma cells, which produced the antibody, contained no trace of radioactively labeled material. It seems that the whole process of combating the antigen is much more complex than one might suppose. It is conducted by a collaboration of groups of cells performing specialized functions. The granule-containing cells that play a temporary role—neutrophils, mast cells and eosinophils—serve mainly to supply enzymes, which they pass on, along with the engulfed antigen, to the macrophages that will attack the antigen. The macrophages themselves react in specialized ways on receiving the dose of antigen. Those that already contain remnants of the same antigen from a previous exposure swell up and then disintegrate. They release substances that intensify the inflammation and attract more cells into the area. These new cells proceed to divide and to produce large amounts of antibody, although they apparently have never encountered the antigen before.

How can we explain the paradox that the antibody is produced not by cells containing information in the form of stored antigenic material but by cells that do not possess this material? We must conclude that the information required to make the antibody is passed on in some way from the former cells to the latter. It seems that the disintegrating cells supply the other cells with something that does two things: stimulates them to divide and causes them to manufacture antibody.

This idea is supported by findings that have been reported by a number of experimenters. For example, Peter C. Nowell of the University of Pennsylvania School of Medicine found that a culture of nondividing blood cells was incited to divide by a protein (that is, an antigen) extracted from beans. When he added the antigen to his culture, it caused many of the cells to clump and then disintegrate; as these broke down, however, the surviving cells were stimulated into active division. Similarly, G. Pearmain and his co-workers in New Zealand have noted that tuberculin (also an antigen) produces the same effect on cultures of cells taken from people who have recovered from tuberculosis. R. W. Dutton and G. Harris of the University of London, after exposing spleen cells to an antigen, extracted a material that could stimulate other cells to divide. And within the past year S. Roath and his colleagues in England reported finding specific antibody globulins in cells that had been prompted to divide by the addition of an antigen to the culture.

We see, then, a consistent general picture. When a cell has been sensitized to an antigen, re-exposure to the same antigen somehow injures the cell and causes it to break down. In doing so it releases a substance or substances that will stimulate other cells to divide and to synthesize specific antibodies that can react with the antigen. What is this stimulating material?

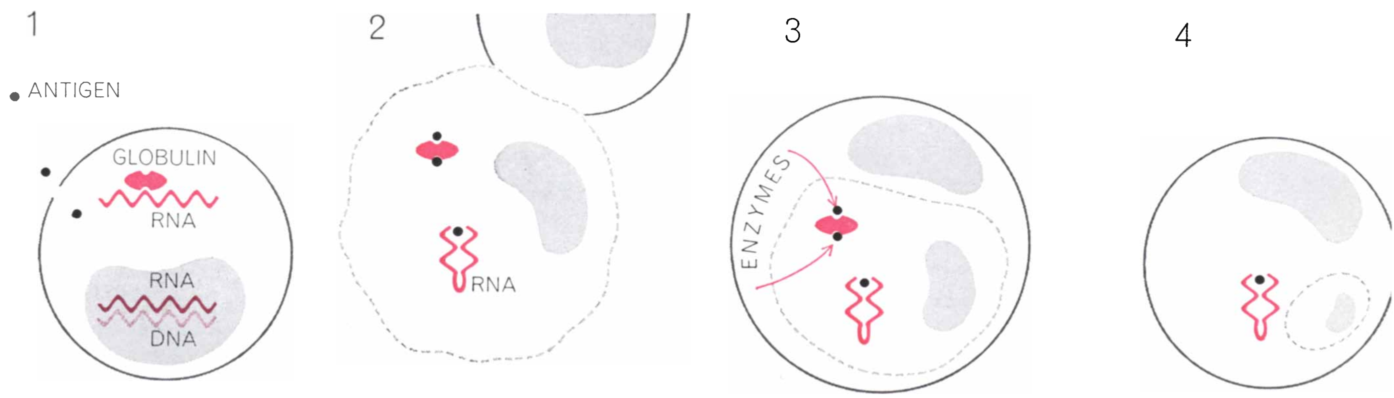
Clearly it involves some component of the antigenic material that is stored—as we have seen—in a sensitized cell. Our



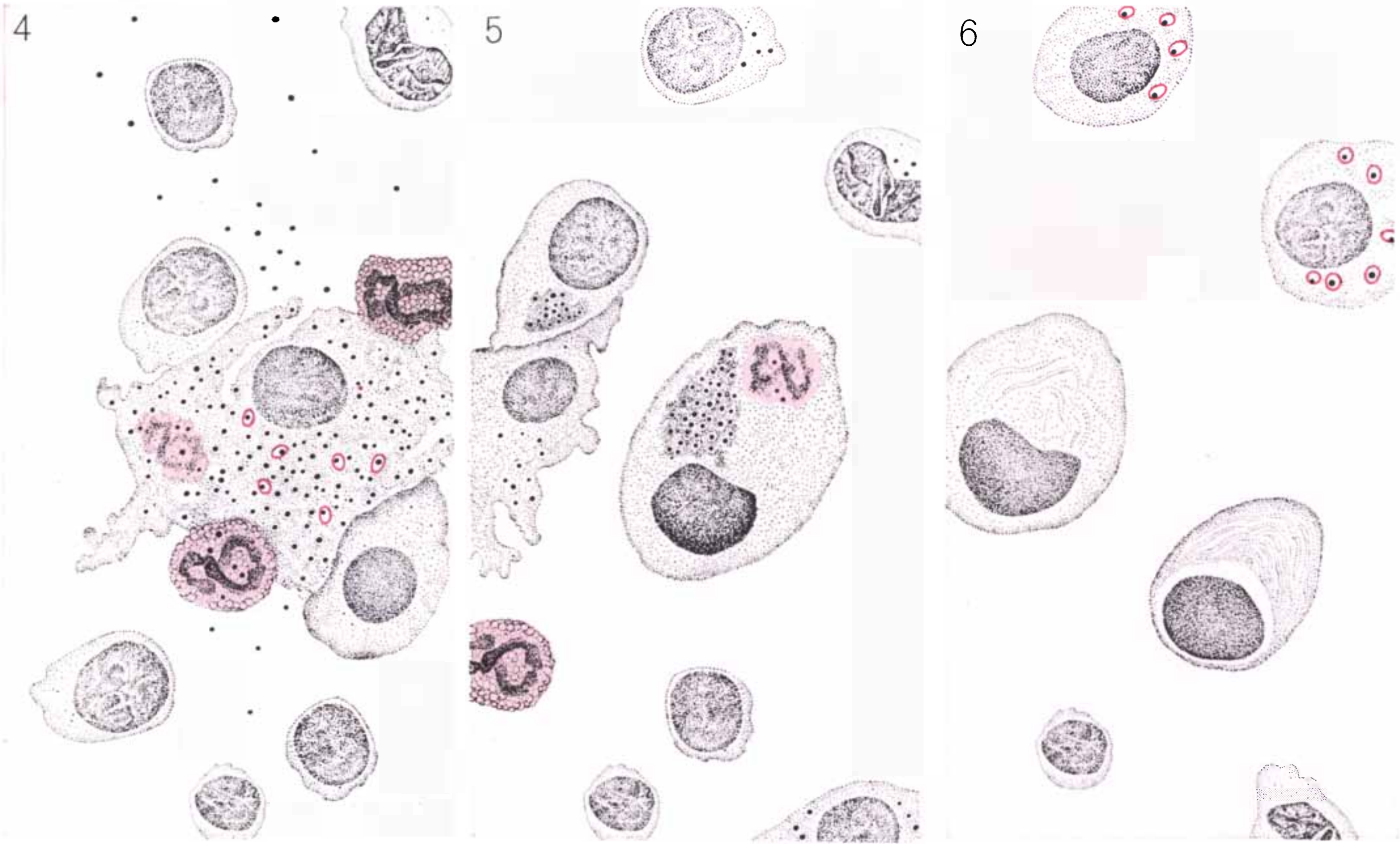
SECONDARY RESPONSE of inflammatory cells to an injection of antigen into a mouse that had been exposed previously to the same antigen is quicker and more violent than the primary response. Neutrophils again arrive at the site first, but not so many of them (*1*). Macrophages, on the other hand, turn up in much greater numbers (*2*). Some of these contain antigen from an earlier

tracer experiments with radioactive antigen show that an active component of the antigen is fixed in some way that prevents it from being completely broken down and allows it to be passed from cell to cell, with the result that it survives in the body for a long time. This suggests that it is attached to, and protected by, an enduring cellular substance.

That substance, according to several indications, is ribonucleic acid (RNA), the substance that presides at the manufacture of proteins in the cytoplasm of cells. In the sensitized macrophages of our experiments we found that the remnant of radioactive antigen was closely associated with a material in the cytoplasm that reacted to stains in the same way as RNA did. And at the California Institute of Technology, Dan H. Campbell and Justine S. Garvey noted that radioactive antigen they had injected into experimental animals was associated with RNA in the cells more than a year later, when they examined the animals' liver cells. At that time they reinjected a new dose of the same antigen,



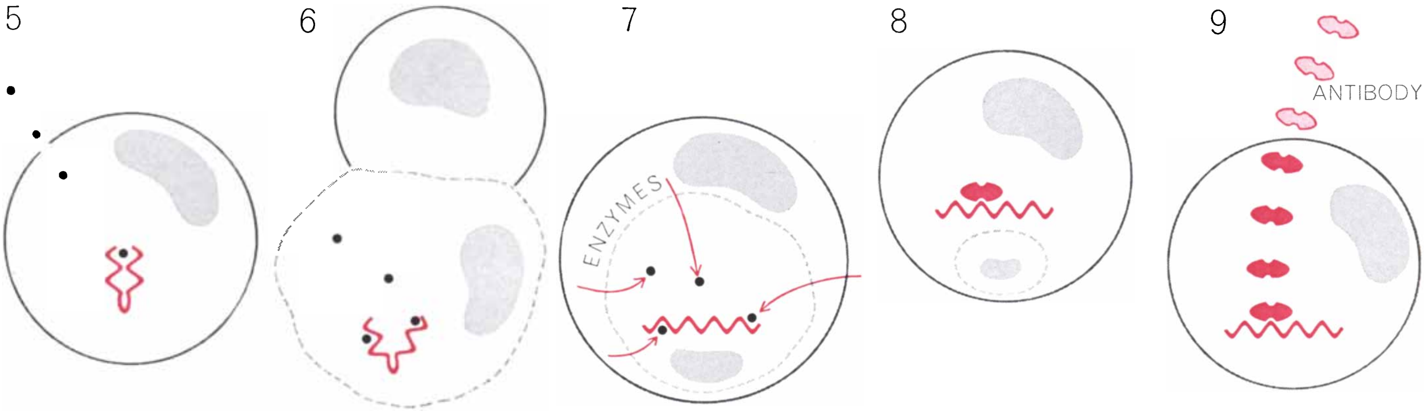
HYPOTHETICAL MECHANISM of hypersensitization and immunity is represented schematically in this diagram. Antigen enters an unsensitized macrophage (*1*), in which the RNA in the cytoplasm is formed on a DNA template in the nucleus. A molecule of globulin formed on the RNA captures and neutralizes two of the antigens (*2*); meanwhile the third antigen combines with the RNA. The cell begins to disintegrate and is engulfed by another macrophage (*3*). Enzymes from the new cell attack and



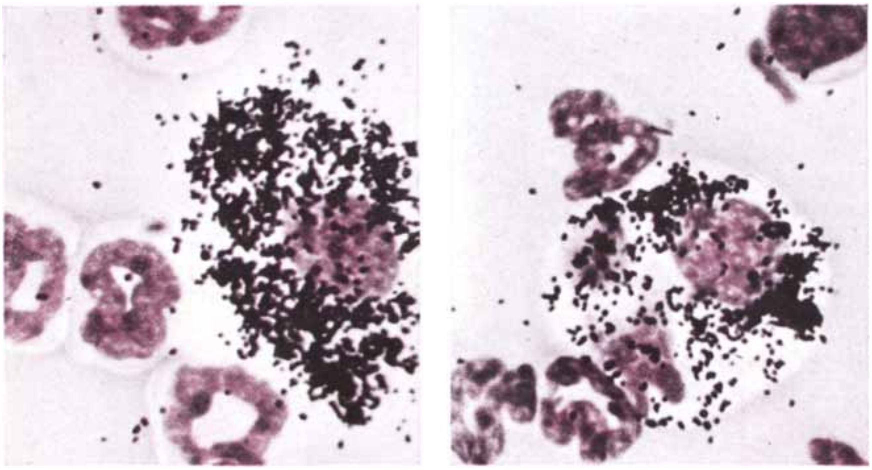
exposure, in combination with RNA (*colored circles around black dots*). These hypersensitive cells attract eosinophils (*3*), which break them open (*4*). More macrophages move into the area and engulf the fragments of broken cells (*5*). Some antigen again escapes destruction in combination with RNA in the macrophages (*6*). Other macrophages are believed to become plasma cells.

this time not radioactive, and the animals then began to excrete radioactive material in their urine. Evidently the old labeled antigen was now being broken down and disposed of. The reappearance of the antigen apparently triggered the separation of the stored antigen from its connection with the protective RNA, presumably by unlocking the connection so that digestive enzymes in the cell could act on it.

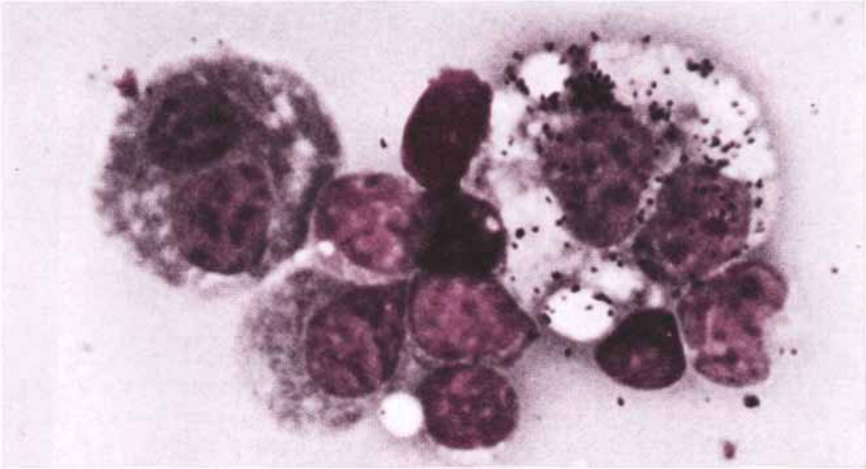
From these facts and assumptions we can draw a rough synopsis that seems to give a reasonable description of the main events in the immune reaction. When an antigen invades the tissues, most of it is soon destroyed by the combined efforts of the various inflammatory cells. Some of the antigen finds a refuge, however, in the macrophages. A molecule of antigen combines somehow with a molecule, or complex of molecules, of RNA. The combination inactivates both the antigen and the RNA; it also makes both invulnerable to the action of enzymes, so that the combined complex is



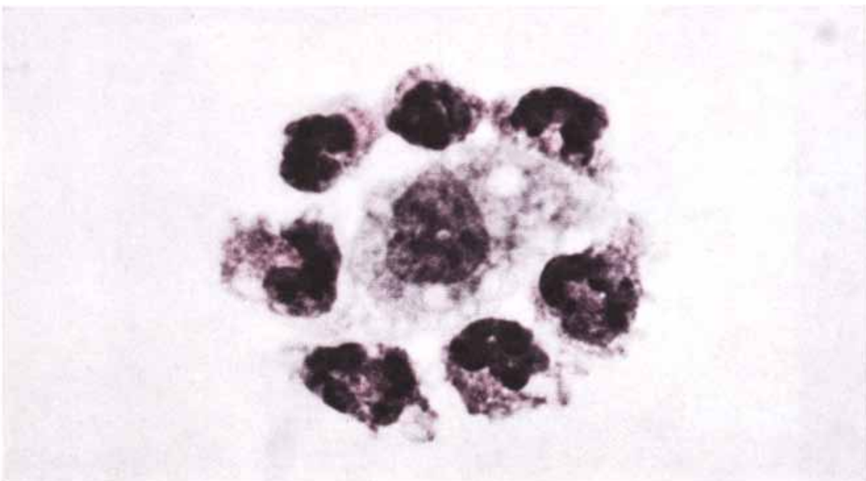
destroy the antigens captured by the globulin, but the antigen-RNA combination remains intact (*4*). A new dose of antigen enters the hypersensitive cell (*5*), breaks up the quiescent antigen-RNA combination (*6*) and triggers the disintegration of the cell, which is in turn engulfed by another macrophage (*7*). Enzymes attack the antigens on the RNA as well as the free antigens in the old cell. The new cell, now a plasma cell, begins to synthesize more globulin (*8*), which becomes antibody outside the cell (*9*).



HYPERSENSITIVE MACROPHAGES react violently on re-exposure to the same antigen. In these micrographs the labeled antigen is from the primary exposure. Both cells are swollen and inactive after being exposed to a second dose of unlabeled antigen. Cell at left is attracting several eosinophils toward its cytoplasm, which is full of labeled antigen. Cell at right has engulfed two eosinophils; two more are attached to its membrane.



TWO BINUCLEATED MACROPHAGES react differently to an injection of antigen. The one at right contains radioactive remnants of the same antigen injected 35 days before; it is swollen and vesiculated and has an eosinophil and several lymphocytes adhering to it. The cell at left contains no radioactive antigen and has not reacted in a hypersensitive manner.



SEVEN EOSINOPHILS surround a hypersensitive macrophage that has just been exposed for the second time to tetanus toxoid (an antigen). Neither dose of antigen was labeled.

not broken down by the normal metabolism of the cells. This antigen-RNA combination, passed along from one generation of cells to the next, may remain intact indefinitely as long as no more antigen appears.

The arrival of more of the same antigen, however, generates a violent reaction. The new antigen breaks up the quiescent antigen-RNA combination. How it does this is not quite clear, but it seems likely that it attacks an active site of the RNA that has remained unoccupied. RNA apparently has two reactive sites. This is indicated by the fact that each antibody molecule formed on the RNA template generally has two active sites, to which it can attach two molecules of antigen. In any event, when a second antigen molecule enters into the antigen-RNA combination, it somehow splits off the first antigen molecule from the RNA. The released antigen molecule is thus exposed to destruction by digestive enzymes, as is the newcomer.

These events have a disastrous effect on the cells in which they take place. The reactions between antigens and cellular antibodies and between antigens and reactivated RNA injure the cell to the extent that it becomes swollen with large bubbles of fluid and soon disintegrates. The bursting cells release inflammatory substances that draw more defensive white cells into the area. The cycle of reactions continues until all the antigen has been destroyed or inactivated. As the inflammation subsides some cells contain active RNA that is prepared to manufacture antibody quickly; others contain antigen-RNA combinations that will react promptly to a new invasion by the antigen.

It seems that the lymphocytes, macrophages and plasma cells may all be morphological variations of the same cell. The cell takes these forms as it carries out its complex series of operations against the antigen, whereas the eosinophils and neutrophils are the carriers that bring to it the antigen and the enzymes it needs to help it do the job.

This comparatively simple concept of the immunological process promises to lead to a more exact understanding of many of the complexities of the process. It will help in the design of further experiments. Among other things, it suggests that it would be rewarding to investigate the reactions between antigens and certain specific substances within cells and the action of enzymes on those complexes.

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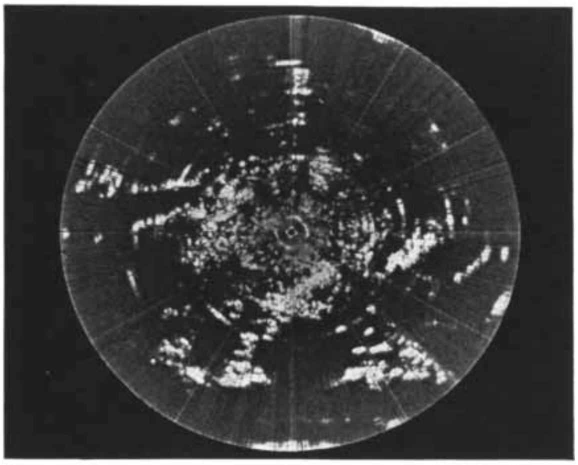
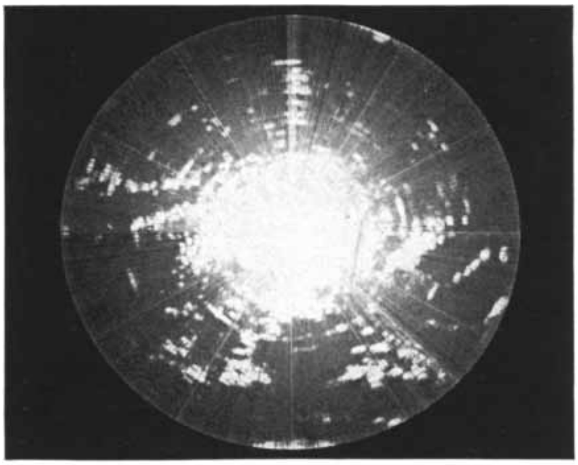


records like the above and not the below.



One can look to Kodak for the electronic circuitry, too. One wants a good record of what the pilot saw, TV or PPI. Or what he might have seen if he didn't have to live in real time. One can be disappointed with arrangements that just steal a picture of a presentation that has been optimized for the human eye.

Airborne radar recorders that do it right are now coming off our production lines. Organizations interested in procuring any type of hardware associated with this problem are advised to get some rough specifications together and put in a call to 716 - 562 - 6000, Ext. 764. The man who will come to the phone will be an electronics engineer employed by the Apparatus and Optical Division of Eastman Kodak Company, Rochester, N. Y. Say, "I saw those two pictures of yours in Scientific American *and—"*

Man is a symbol-using animal

As far as we are concerned, the eyes have it. The eye is the gateway to the soul. When a blind man says "I see," he means "I understand." Literal seeing is preferred by billions to figurative seeing. Therefore where understanding is required, as in science and engineering, means are ever sought to use photography to best advantage.

Of course, photography covers more than the photographing of objects. Often it is very desirable to photograph symbols such, for example, as are drawn in some fashion or other by electronic pencil. To do such photography on more than a manual, casual basis we furnish a 16mm and 35mm film long known to those skilled in the art as KODAK LINAGRAPH Pan Film. Time has caught up with it, though, as we are pleased to be telling you instead of having you tell us.

The old LINAGRAPH Pan emulsion couldn't stand more than 90°F processing temperature. To be in the swim today, one processes film almost as hot as one launders shirts. Minutes shrink to seconds (but the shirts hardly shrink at all any more). Now KODAK LINAGRAPH Pan Film carries the legend "Improved for High-Speed Processing." It can stand 130°F.

We don't merely guarantee that the emulsion will not turn to beef bouillon at 130°F. We tell you that the photographic quality will be just as good and better than when you carefully maintained 68°F, as you were taught in youth, when there was plenty of time.

Arrangements to shoot the new KODAK LINAGRAPH *Pan Film to you are made through Photorecording Methods Division, Eastman Kodak Company, Rochester, N. Y. For 16mm, we can also furnish a processing machine that delivers in 2 minutes, dry to dry. For 35mm, there is still a little challenge left in designing 130°F processing gear instead of the easy way, where you simply make out a $12,500 equipment-purchase requisition.*

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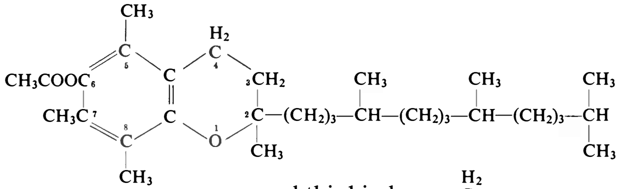
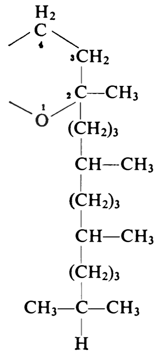


and this kind:



Both of these configurations exhibit the tangle of biological effects conveniently named "vitamin E." One exhibits much more vitamin E effect than the other. Do we charge more for that one? No, sir or madam. The biologically more effective one, on the commodities market, costs about 1/2000 as much as the less effective one.

In isolating the weak one and offering it for experimental use, we think, however, that we have done a fine thing.

Only one of the above configurations has ever been found in nature*—the bargain-priced *d*-α-tocopheryl acetate. Our own investigations (*Biochemistry 2*, 188 (1963)) indicate that the *l*-epimer has only 21% as much biopotency, as measured by resorption-gestation bioassay with vitamin E-deficient female rats. Other laboratories, comparing on the basis of erythrocyte hemolysis in rats, are also finding a low *l*:*d* biopotency ratio.

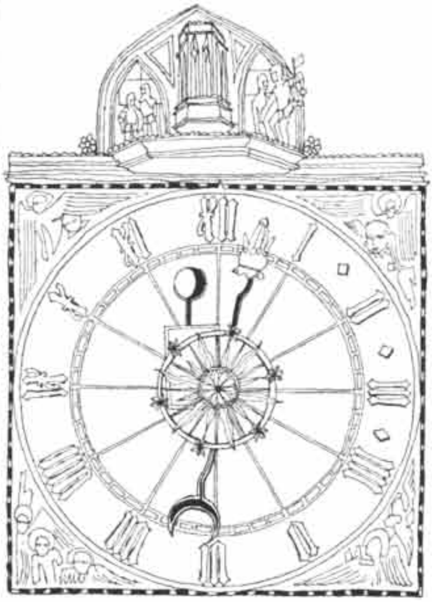
Further studies of other vitamin E-deficiency symptoms and with other species will be well worth doing. Data on the low effectiveness of the *l*-epimer may shed light on the mechanisms by which the natural form, *d*-α-tocopherol, does its work in animals and men.

We aren't trying to do it all. Others are welcome to this lively subject. For ½ gram of l-α-Tocopheryl Acetate *as* EASTMAN *Organic Chemical No. 9170 send $65 to Distillation Products Industries, Rochester, N. Y. 14603 (Division of Eastman Kodak Company), which has research laboratories staffed with people who like to correspond about vitamin E.*

* In nature C_6 carries a hydroxyl instead of an acetyl radical. For pharmaceutical and animal-husbandry applications, the acetyl completely protects the molecule from oxidation, without further protective measures. The acetyl is hydrolyzed off by the esterases in the digestive tract. Without the acetyls, these two kinds of tocopherol can act chemically as antioxidants; they have equal antioxidant activity.

Prices subject to change without notice.

SCIENCE AND



End of Overkill?

The U.S. and the U.S.S.R. have taken two steps that, following the nuclear-test-ban treaty, continue the slow evolution of control of the arms race. The U.S. indicated that, for the first time since it began to manufacture fissionable materials in 1943, it would cut back the production of these materials. The U.S.S.R. said that it was reducing its 1964 defense budget by the equivalent of $660 million.

President Johnson announced the U.S. move in his first State of the Union Message. He said: "We are cutting back our production of enriched uranium by 25 per cent; we are shutting down four plutonium piles."

A major force behind the move appeared to be acceptance of the fact that the U.S. has reached, or is approaching, the point of "overkill" with its nuclear arsenal: the point at which there are more than enough weapons to destroy any enemy nation. In announcing the cutback the President declared that "we must not stockpile arms beyond our needs, or seek an excess of military power that could be provocative as well as wasteful."

Earlier Secretary of Defense McNamara had outlined for the North Atlantic Treaty Organization the size of the U.S. nuclear arsenal. He said the U.S. now has some 2,000 nuclear warheads ready for immediate delivery at long range, among them more than 500 intercontinental missiles; he added that the U.S. would have more than 1,500 such missiles by 1966. From other sources came data putting the number of missiles emplaced in the continental U.S. at 587, of which 237 are liquid-fueled Atlas and Titan types with a range of 8,000 to 9,000 miles and 350 are solid-fueled Minuteman types with a range of 5,000 miles. In addition the U.S. has 10 operational Polaris submarines, each capable of carrying 16 missiles, and more than 500 Strategic Air Command aircraft ready for quick action. Beyond this arsenal are tens of thousands of nuclear warheads for smaller weapons.

Moscow's reduction in defense spending, announced in December, amounted to 600 million rubles in a defense budget of about 13.3 billion rubles. The reduction was therefore modest, but it was the first in several years.

The Smoking Report

"Cigarette smoking is causally related to lung cancer in men; the magnitude of the effect of cigarette smoking far outweighs all other factors."

This unqualified statement in the report issued January 11 by the Public Health Service answered a question that had been debated for more than a decade. The conclusion was reached by the 10 members of the Surgeon General's Advisory Committee on Smoking and Health, which had been appointed in 1962.

The first large-scale statistical studies showing the harmfulness of cigarettes were published in 1954 by the British physicians W. Richard Doll and A. Bradford Hill and independently by E. Cuyler Hammond and Daniel Horn of the American Cancer Society [see "The Effects of Smoking," by E. Cuyler Hammond; Scientific American, July, 1962]. In the nine years since these studies were reported more than 300,000 Americans have died of lung cancer. According to the Surgeon General's committee about 90 per cent of these deaths were caused by cigarette smoking. Throughout the nine-year period the cigarette industry placed its faith in a single argument: A statistical association between cigarette smoking and disease does not prove a cause-and-effect relation.

The committee, selected from men who had never been involved in the controversy, said that it "was aware that the mere establishment of a statistical association between the use of tobacco and a disease is not enough." It reached its judgment that cigarette smoking and lung cancer are causally related after "prolonged study and evaluation of many lines of converging evidence." This evidence included animal experiments showing that cigarette smoke impairs the ability of cilia in the bronchial tract to eject foreign substances. Another converging line of evidence was autopsy studies that revealed extensive cellular changes in the lungs of cigarette smokers but not in nonsmokers.

In issuing the report Surgeon General Luther L. Terry said that "appropriate remedial action" would be taken by Government agencies. The Federal Trade Commission is believed to have the power, even without Congressional action, of requiring a warning label on cigarette packages. A second study group will be appointed to make public policy recommendations that may affect the $8-billion-a-year U.S. cigarette industry in other ways.

Lively Moon

Five U.S. astronomers at two observatories have recently seen transient luminous red spots on the moon. James A. Greenacre has announced in *Sky and Telescope* that last October 29 he and Edward Barr, working with the 24-inch refracting telescope at the Lowell Observatory in Flagstaff, Ariz., saw three red spots lasting less than 20 minutes, one on the rim of the crater Aristarchus and the other two in the nearby Schröter's Valley. On November 27 Greenacre again observed a glowing red spot some 12 miles long and a mile and a half wide on the rim of Aristarchus. John S. Hall, director of the observatory, and Fred Dungan, another astronomer, also saw it. Hall called Peter A. Boyce of the Perkins Observatory a few miles away and told him that there seemed to be some kind of activity near Aristarchus, but he did not specify exactly where. Boyce trained the 69-inch reflector of his observatory on the crater and found the spot. It faded out about an hour and a quarter after it was first observed.

Until recently it was thought that the surface of the moon is totally inactive in the geological sense, although "obscurations" in one section of Schröter's Valley had occasionally been reported. Then in 1958 the Soviet astronomer Nikolai A. Kozyrev told of observing a glow from the central mountain peak in the crater Alphonsus. Astronomers in the U.S., however, were unable to confirm this observation. Last year Kozyrev said that twice late in 1961 he had observed what might have been an eruption of molecular hydrogen from the center of Aristarchus, which is one of the brightest features on the moon.

Harold C. Urey of the University of California at La Jolla has suggested that the red glow may be due to a form of carbon not present on the earth. The carbon could originate with the action of water on calcium carbide below the surface of the moon, which could release acetylene gas that would be broken down by sunlight at the surface. Both U.S. observations were made less than two days after Aristarchus had emerged from the dark side of the moon into the light of the sun.

Medieval Hormone Chemistry

A recently translated Chinese document dating from the 16th century indicates that the practice of prescribing steroid sex hormones for hormone-deficient patients may have been established in China some 1,000 years ago. According to Lu Gwei-Djen and Joseph Needham of the University of Cambridge, detailed directions for making androgen (the male sex hormone) and estrogen (the female hormone) from urine and other ingredients are contained in Chapter 52 of *Pên Tshao Kang Mu,* a compendium of pharmaceutical preparations written by Li Shih-Chen in 1596. The six recipes translated by Lu and Needham and discussed in a recent article in *Nature* all date from older books that are either no longer extant or extremely rare; the oldest of these is *Ching Yen Fang* (*Tried and Tested Prescriptions*) by Chang Shêng-Tao, which dates from about 1025.

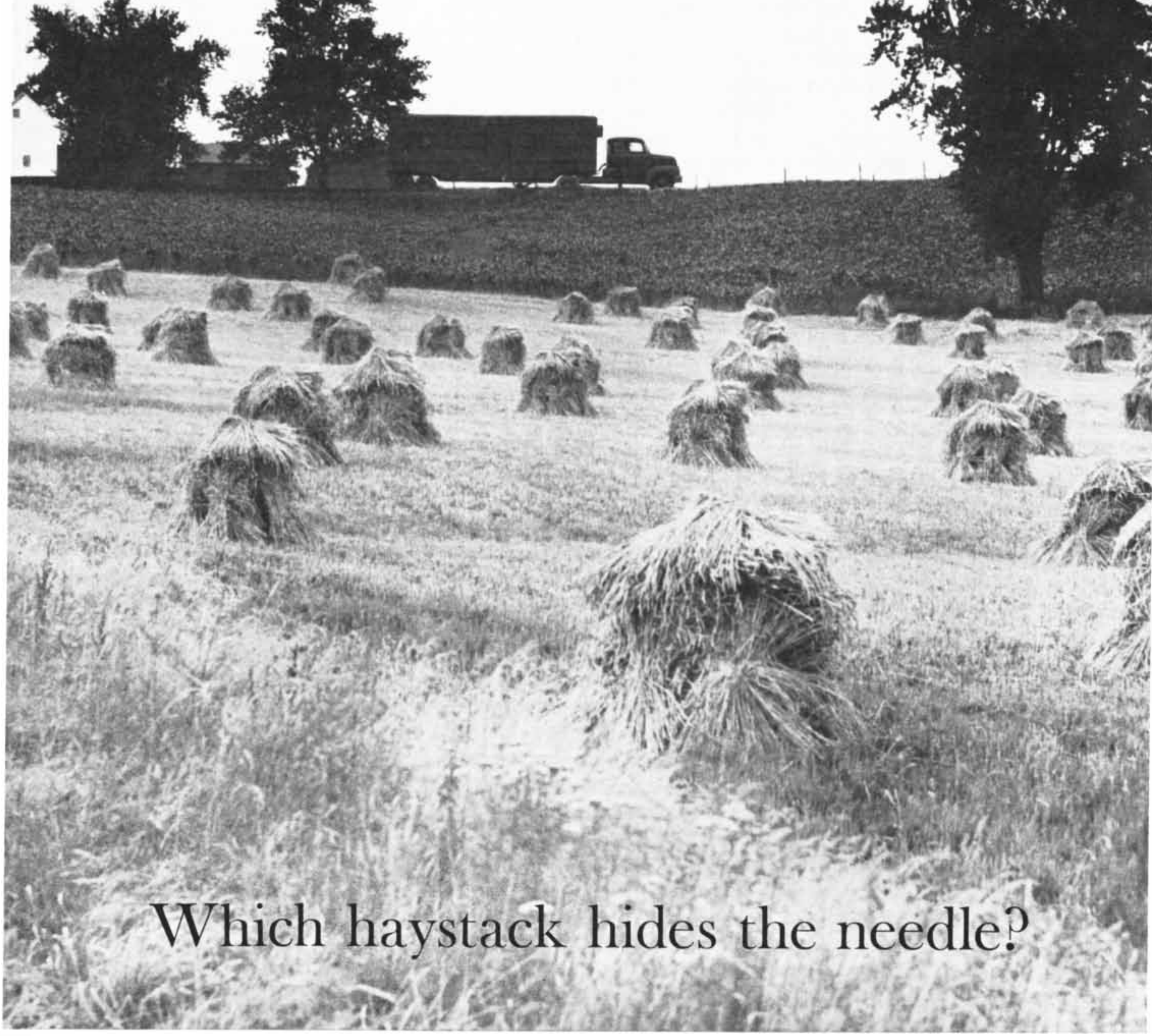
All six methods for preparing the hormones start with large quantities of urine (as much as 300 gallons) from adults or adolescents of either sex. The simplest and possibly the oldest method was to boil away everything but the solids, which included a large proportion of impurities. Most of the other methods, however, employed substances that caused the precipitation of a much purer product. Among these substances were calcium sulfate and the juice of the soap-bean tree (*Gleditschia sinensis*), the bean juice being added to the urine at the rate of "one bowlful for every tub." The precipitate was then placed in boiling water in order to separate the soluble from the insoluble steroids. The steroid mixtures thus obtained were usually further purified by heating them carefully in small earthenware pots with porous covers. Since the urinary steroids have sublimation temperatures ranging from about 140 degrees centigrade to about 280 degrees, with considerable gaps between different types, careful attention to the degree and duration of heating would result in quite pure products. This technique of purification by sublimation is known to have been mastered by Chinese alchemists as early as the second century B.C. The typical final product is described in the old texts as being either white, crystalline, glittering and lustrous or pearly like translucent jade. In some cases the hormones were emulsified with milk fat before being administered.

The modern discovery that urine, particularly the urine of pregnant women, contains sex hormones and that these hormones could be recovered was not made until 1927. Nonetheless, Lu and Needham believe this achievement was not inconsistent with the general state of scientific thought in medieval China. They point out that "classical Chinese medical and physiological theory envisaged a constant interaction of the organs of the body mediated through the circulating blood. Since the urine was considered as 'of the same category as' (*thung lei*) the blood, then the virtues emanating from the organs might perhaps be found in it also."

Boost for Fossil Fuels

Although it is often predicted that nuclear power plants will produce electricity more cheaply than fossil-fuel plants within the next decade, the forecast may be upset by the emerging technology of magnetohydrodynamic power generation. In a magnetohydrodynamic generator a current is produced when a moving stream of an electrically conductive gas cuts the lines of force in a magnetic field. In a conventional generator a solid conductor, in the form of copper wire, moves through a magnetic field.

Studies by the Central Electricity Generating Board in Great Britain indicate that magnetohydrodynamic generators may be able to raise the efficiency of fossil-fuel power plants more significantly than that of nuclear power plants. The reason is that magnetohydrodynamic units are potentially capable of operating directly on the combustion



It's hard enough to find a needle in one haystack. But it *really* gets difficult when the needle moves from stack to stack.

This analogy describes the concept behind a new kind of missile system now being developed: MMRBM—Mobile Mid Range Ballistic Missile.

Take an advanced, highly-accurate missile. Put it into a compact, self-contained "package"—from which it can be launched at a moment's notice. Then move it where you want it.

Like our peripatetic needle, the unique advantage of MMRBM is in its mobility; for example, mounted on a "semi" truck trailer. The total mobility of the weapon system enables units to be parked at widely dispersed parking areas and moved frequently or to operate in a continuously mobile fashion over highways and secondary roads. Widely dispersed and moving in unpredictable patterns, these MMRBM's would be virtually impossible to keep under surveillance and to target. No economical defense can now be visualized.

These MMRBM "packages" would also be "air-liftable." Stockpiled at strategic points, they could be put aboard jet transports and be delivered to trouble spots in hours.

Throughout human history, man has recognized the need to provide for his and his neighbor's safety through strength. The MMRBM system—versatile, flexible, economical—adds a new dimension

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gases of a fossil-fuel furnace, which are much hotter than the gases that can be produced in a nuclear reactor. Efficiency of power generation is proportional to temperature. In a furnace, flame temperatures can exceed 2,000 degrees centigrade; the exit-gas temperature from reactors now being built in Britain will be 410 degrees C. and that for the experimental British Dragon reactor will be only about twice that. The efficiency of a power plant operating at 410 degrees is about 33 per cent, compared with about 40 per cent for a modern coal or oil power plant.

To raise the fossil-fuel efficiency still higher P. R. Howard of the Central Electricity Research Laboratories in Leatherhead, England, has proposed in the *New Scientist* that hot furnace gases should be fed first into a magnetohydrodynamic generator and then into a boiler to make steam. If about a quarter of the heat were extracted in the magnetohydrodynamic generator, the overall plant efficiency might be raised from about 40 to 55 per cent. Experimental magnetohydrodynamic generators at the Leatherhead laboratory have operated with combustion gases at 2,700 degrees C.

Supernova Electrons

Balloon observations by physicists at the University of Chicago and the Argonne National Laboratory have yielded the first experimental evidence to support the idea that cosmic rays originate in the explosions of supernovae. The primary cosmic rays that plunge into the earth's atmosphere and give rise to showers of nuclear debris at the ground consist almost entirely of protons, or hydrogen nuclei. Certain observations of radio astronomy have indicated, however, that also present in the primary cosmic radiation are large numbers of electrons. Two theories have been put forward to account for the electrons: that they arise in the collision of protons with hydrogen nuclei in interstellar space and that they are generated by supernovae. The first process would manufacture roughly equal numbers of negative electrons and positrons (positive electrons); the second, a preponderance of negative electrons.

Last summer, according to their report in *Physical Review Letters,* James A. De Shong, Jr., of the Argonne Laboratory, Peter Meyer of the University of Chicago and Roger H. Hildebrand, who is affiliated with both institutions, set out to measure the relative numbers of negative electrons and positrons in the primary cosmic radiation. At Fort Churchill in Manitoba they sent up balloons on July 28 and August 5, each balloon remaining at an altitude of some 25 miles for more than 10 hours. There, above virtually all the earth's atmosphere, cameras in the apparatus carried aloft by the balloons recorded 62,000 events, or cosmic ray passages. A permanent magnet caused negative electrons and positrons to take slightly different paths through the spark chambers that detected them.

The photographs revealed a ratio of three negative electrons to every positron. At higher energies, between 300 million and a billion electron volts, the ratio of negative electrons to positrons reached five to one. The figures are interpreted to mean that about half of all the primary cosmic-ray electrons come from proton-proton collisions in space and half from supernovae.

Spiraling Spheres

One would expect a smooth spherical body released in still air or water to fall straight down. Apparently it does not. It oscillates, tracing a path like an irregular corkscrew. Uri Shafrir, an Israeli physicist visiting the University of California at Los Angeles, discovered the phenomenon about a year ago; since then he has been investigating it in the laboratory and in the field.

In the laboratory Shafrir drops spheres up to an inch in diameter from the top of a tank 10 feet high, three feet in diameter and filled with distilled water. He photographs the falling sphere with a still camera equipped with stroboscopic flash and a mirror system that splits the field to provide two perpendicular views of the sphere and thus record its travels in three dimensions. The oscillations show up clearly on the pictures made against a ruled background; their amplitude is of the order of several sphere diameters and their "wavelength" is some 10 or 50 diameters, depending on the size and weight of the sphere. To test these observations in the atmosphere Shafrir dropped spherical metal shells six to 16 inches in diameter from helicopters hovering at 10,000 feet. Tracking by radar and motion picture theodolites yielded data that recorded the position of the spheres every tenth of a second. The oscillations have proved to be much greater in the atmosphere than in water: up to several hundred feet in amplitude and several thousand in wavelength.

Shafrir still does not know why falling spheres oscillate, although he assumes it must have something to do with the flow of water or air around them. In an attempt to visualize this flow he put smoke generators inside some of the metal spheres and allowed the smoke to escape through small holes in the surface. He is now analyzing high-speed motion pictures of the smoke trails to see if the pattern of vortexes and the manner in which the vortexes are shed behind the spheres yield evidence about the flow of air and therefore about the origin of the oscillations.

Replanted Teeth

Techniques for replanting knocked-out teeth and for transplanting teeth within the owner's mouth have been reported by Sidney R. Kupfer of the New York University College of Dentistry. According to Kupfer, a tooth can be replanted as much as two days after it has been dislodged. It should be kept moist during that time; the best way to do so is to put it into a container of water. Although the replanted tooth will not be alive, it will remain in place for many years. The technique is therefore particularly useful with children, inasmuch as a permanent prosthesis is out of the question for them because their bones are still growing. With older people, if dental facilities are poor, the technique can be used to remove, treat and replant infected molars until it is possible to replace them with bridgework.

Kupfer prepares a tooth for replanting by removing the pulp, filling the root canal and disinfecting the tooth. Then, having cleaned and disinfected the socket, he replaces the tooth in the socket and splints it to an adjoining tooth with a quick-setting plastic material. The splint can be removed in about six weeks; by then the tooth has begun to fuse to the jawbone. Eventually the root will dissolve and the tooth, no longer held by the bone, will come out again. That, however, should not happen for a dozen years or more.

A transplant, according to Kupfer, can be used to replace a diseased or broken tooth, perhaps even a missing tooth. If the patient is under the age of 20, an unerupted and immature wisdom tooth can be transplanted. Such a tooth, having an open root end, can draw an adequate blood supply and will remain alive in the new location. In an older patient, an unerupted wisdom tooth can be transplanted, but such a tooth is likely to be so fully formed that it will die for lack of an adequate blood supply. Still, it would be "functional and aesthetic" in the new location for a long time.

STRONGLY INTERACTING PARTICLES

Presenting an account of recent developments in high-energy physics. These particles that respond to the strongest of the four natural forces no longer seem "elementary." They may be composites of one another

by Geoffrey F. Chew, Murray Gell-Mann and Arthur H. Rosenfeld

Only five years ago it was possible to draw up a tidy list of 30 subatomic particles that could be called, without too many misgivings, elementary. Since then another 60 or 70 subatomic objects have been discovered, and it has become obvious that the adjective "elementary" cannot be applied to all of them. For this reason the adjective has been carefully avoided in the title of this article. There is now a widespread belief among physicists that none of the particles with which this article is mainly concerned deserves to be singled out as elementary.

What is happening has happened before in physics: the old way of looking at things, which was adequate for perceiving order in a limited number of observations, finally proved cumbersome and inadequate when the accuracy and range of observation increased. This happened with the Ptolemaic scheme of epicycles for describing the motions of the planets. Much the same thing occurred early in this century when spectroscopists, studying the light emitted by excited atoms, found a profusion of discrete wavelengths that were at total variance with the wavelengths predicted by classical electrodynamics. The spectroscopists accumulated so much empirical information, including sets of "selection rules" governing the permissible states of excited atoms, that it finally became possible in 1926 for Werner Heisenberg, Erwin Schrödinger and others to formulate a new mechanics—quantum mechanics—capable of predicting most of the states of matter on the atomic and molecular scale.

A similar situation may exist today in particle physics. The great unifying invention analogous to quantum mechanics is still not clearly in sight, but the experimental data are beginning to fall into striking and partly predictable patterns. What can be said to summarize the vast amount of particle information now available?

First of all, there is a clear distinction between strongly interacting particles, such as the neutron and proton, and other particles. The neutron and proton are known to interact through the strong, short-range nuclear force, which is responsible for the binding of these particles in atomic nuclei. All particles discovered to date participate in this strong interaction except the photon (the particle of light and other electromagnetic radiation) and the four particles called leptons: the electron, the muon (or mu particle) and the two kinds of neutrino.

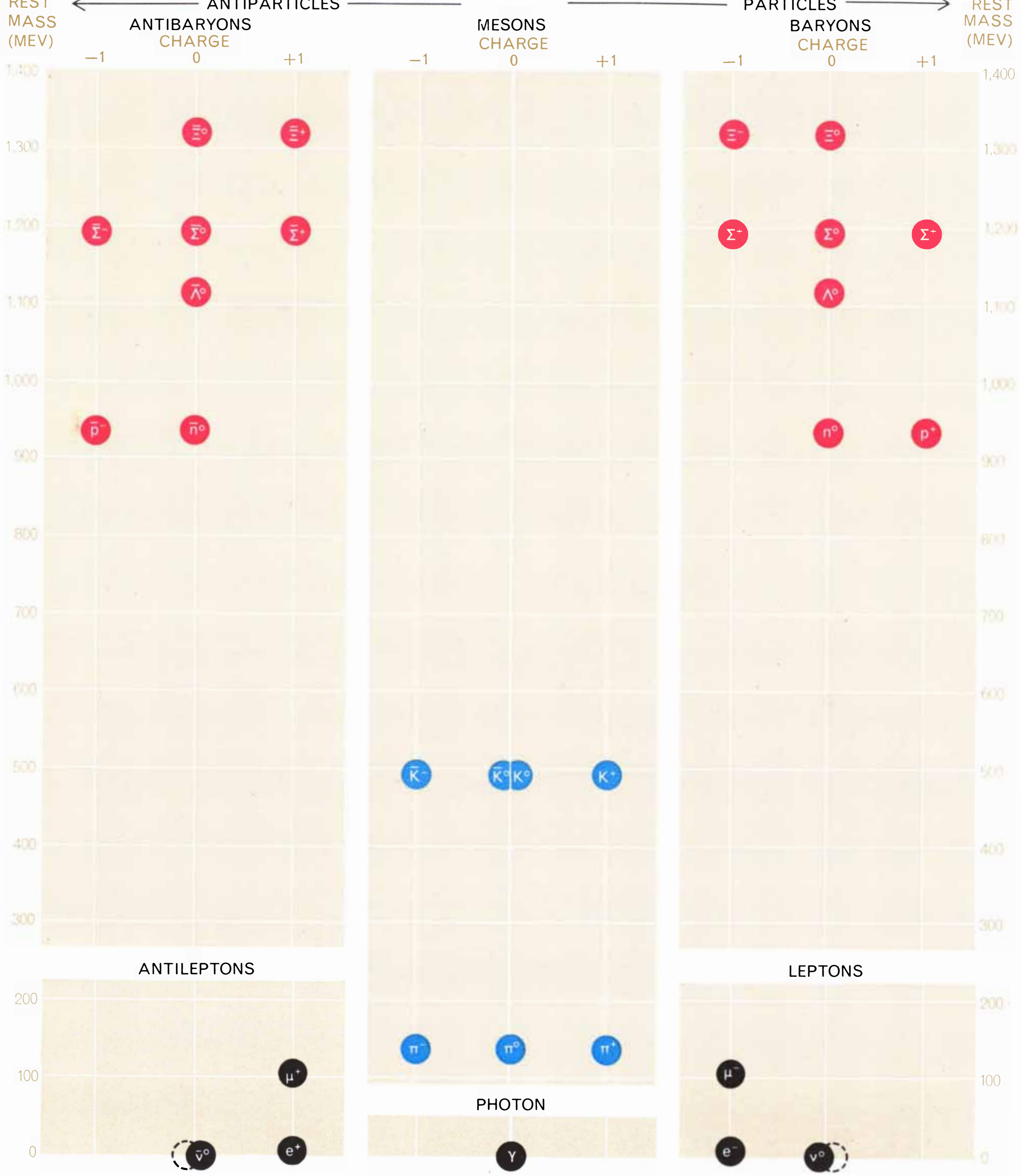
Another striking property of the strongly interacting particles is that none of them has a small rest mass. Rest mass is the mass that a particle would have if it were motionless; this is the minimum mass the particle can have. It is now common to express this mass as its equivalent in energy, rather than in units of the electron's mass, as was often done in the past. The lightest strongly interacting particle is the pion (or pi meson), which has a mass with an energy equivalent of some 137 million electron volts (Mev). In contrast, the mass of the electron is about .5 Mev and that of the photon and the neutrinos is believed to be zero.

A third general observation is that the recent proliferation of particles has so far occurred almost exclusively among the strongly interacting particles. Although this proliferation came as a surprise to physicists, a precedent for this state of affairs can be found in ordinary atomic nuclei. It is well known that all compound nuclei, from the nucleus of deuterium (heavy hydrogen) to those of the heaviest elements, can exist at a variety of energy levels, comprising a "ground" state and many excited states. These levels, which can be detected in several ways, indicate different degrees of binding energy among the component nucleons (neutrons and protons) in the nucleus. The binding energy, of course, is an expression of the strong nuclear force.

It is now clear that the nuclear force can similarly give rise to numerous states among those strongly interacting particles sometimes designated elementary. The lower states are "bound," or stable; the higher states are only partly bound, or unstable, decaying in a tiny fraction of a second. The result is that all strongly interacting particles exhibit a spectrum of energy levels with no sharp upper limit.

Since the leptons do not participate in strong interactions, it is not surprising that their spectrum of states, beginning with the massless neutrino and apparently terminating sharply at the muon, with a mass of 106 Mev, bears no resemblance to any known dynamical spectrum. In recent years physicists have learned much about the simplicity and regularity in the properties of leptons, but they have learned nothing of why these particles exist.

In the following discussion we shall begin by considering the place of the strong force in the hierarchy of four forces that seem to underlie all the operations of the physical universe. Next we shall describe a new nomenclature that assigns each of the strongly interacting particles to one of a small number of families, each characterized by a distinctive set of properties. One group of these families embraces the baryons, which in general are the heaviest particles; a second group consists of mesons, the first members of which to be discovered were lighter than the baryons. The new naming system will require a brief review of the seven quantum num-

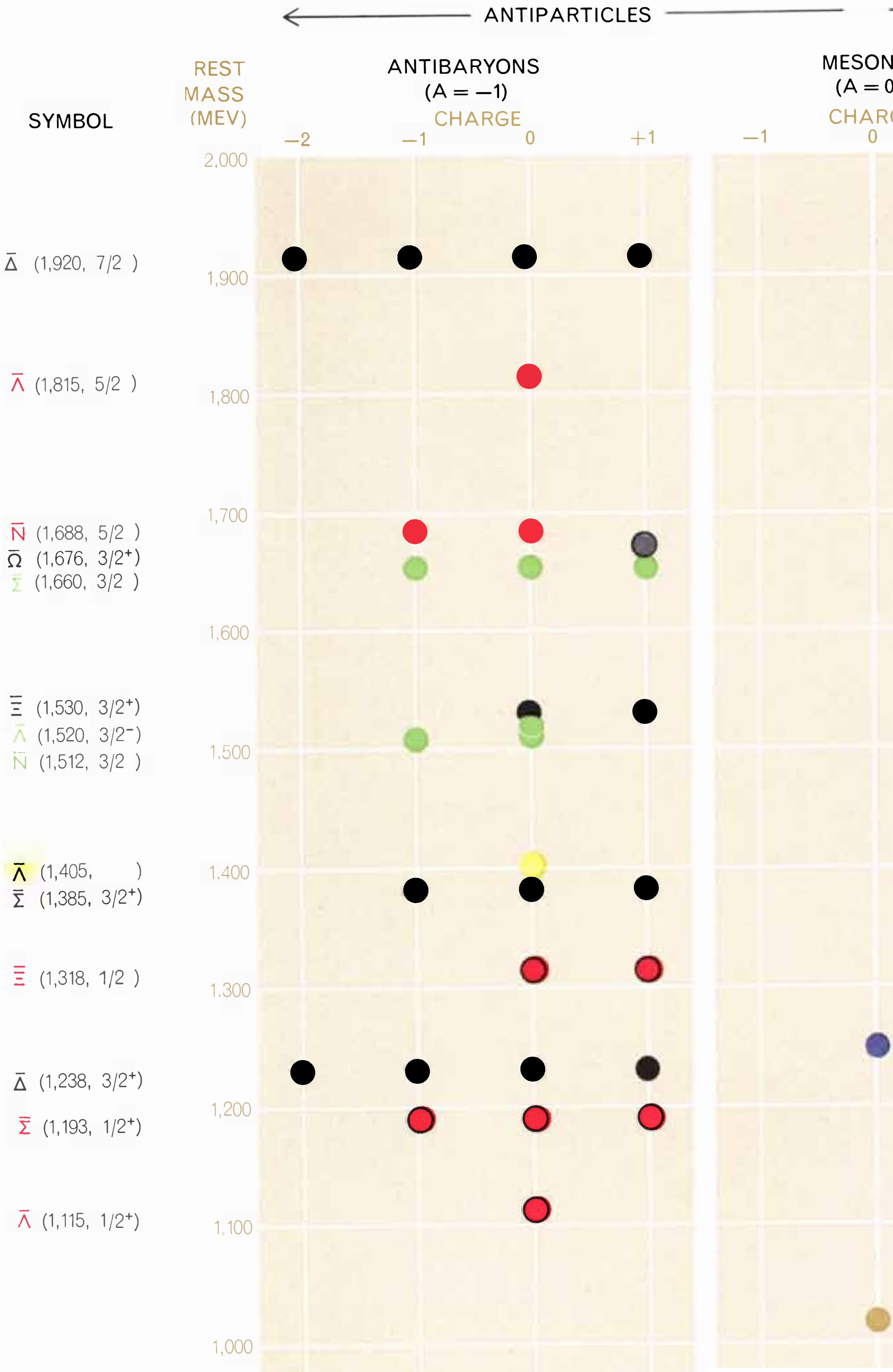


BARYONS
Ξ XI
Σ SIGMA
Λ LAMBDA
n NEUTRON
p PROTON

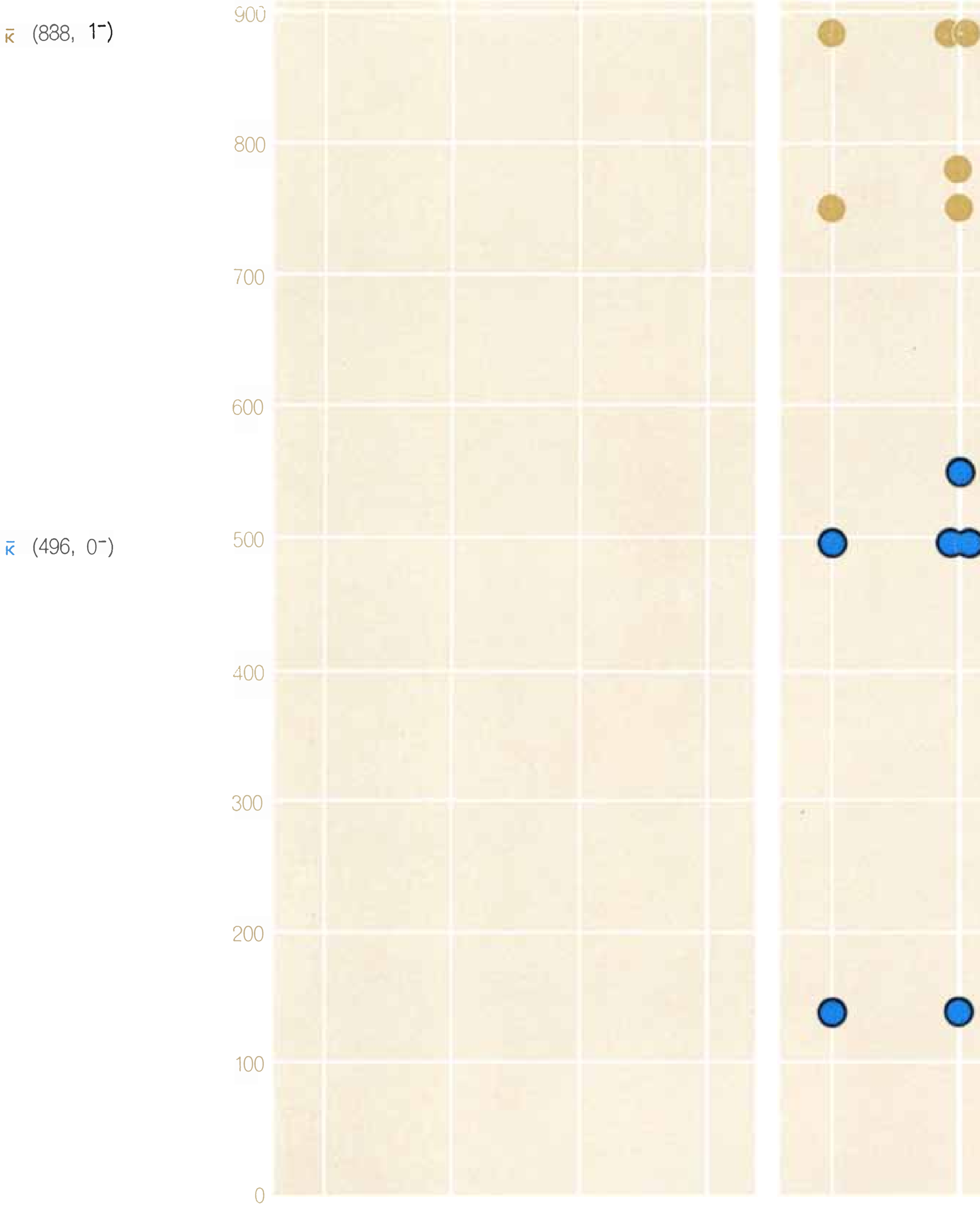
MESONS
K K MESON, OR KAON
π PI MESON, OR PION

LEPTONS
μ MU, OR MUON
e ELECTRON
ν NEUTRINO

THIRTY PARTICLES of 1957 consisted of 16 baryons and antibaryons, seven mesons, six leptons and antileptons and the photon. (Baryon, meson and lepton respectively signify heavy, medium and light particles.) The strongly interacting particles, which respond to the strong, or nuclear, force, are in color. Particles shown in black do not respond to this force. It is the former that have proliferated in the past half-dozen years, as shown on the next two pages. In the same period the number of leptons and antileptons has increased by only two. It is now known that there are two kinds of neutrino instead of one, each with its own antiparticle (indicated by broken lines next to the two particles known in 1957). One other neutral and massless particle is believed to exist but is not shown here: the graviton, the carrier of the gravitational force. The hypothetical carrier of the weak force, also not shown, should have a considerable mass and one unit of electric charge. Evidence for it is now being sought.



ANTIPARTICLES
SYMBOL
REST MASS (MEV)
ANTIBARYONS (A = −1)
CHARGE
−2
−1
0
+1
MESON
(A = 0
CHARG
−1
0
2,000
Δ̄ (1,920, 7/2)
1,900
Λ̄ (1,815, 5/2)
1,800
1,700
N̄ (1,688, 5/2)
Ω̄ (1,676, 3/2⁺)
Σ̄ (1,660, 3/2)
1,600
Ξ̄ (1,530, 3/2⁺)
Λ̄ (1,520, 3/2⁻)
N̄ (1,512, 3/2)
1,500
Λ̄ (1,405,)
Σ̄ (1,385, 3/2⁺)
1,400
Ξ̄ (1,318, 1/2)
1,300
Δ̄ (1,238, 3/2⁺)
Σ̄ (1,193, 1/2⁺)
1,200
Λ̄ (1,115, 1/2⁺)
1,100
1,000



BARYONS
Ξ XI
Σ SIGMA
Λ LAMBDA
N (NUCLEON)
Δ DELTA
Ω OMEGA

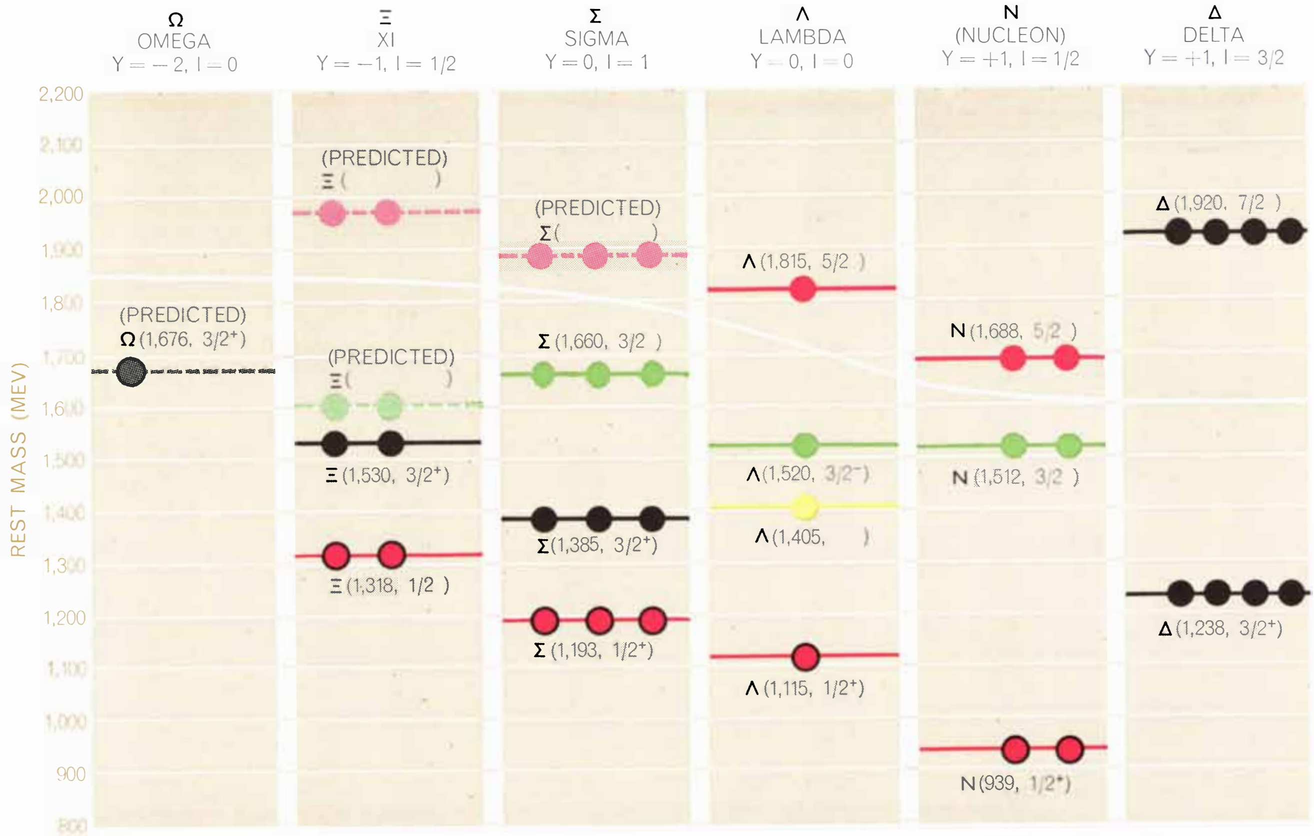
MESONS
η ETA
π PI
κ̄ ANTIKAPPA
κ KAPPA

COLLOQUIAL NAMES
φ PHI
ω OMEGA
ρ RHO

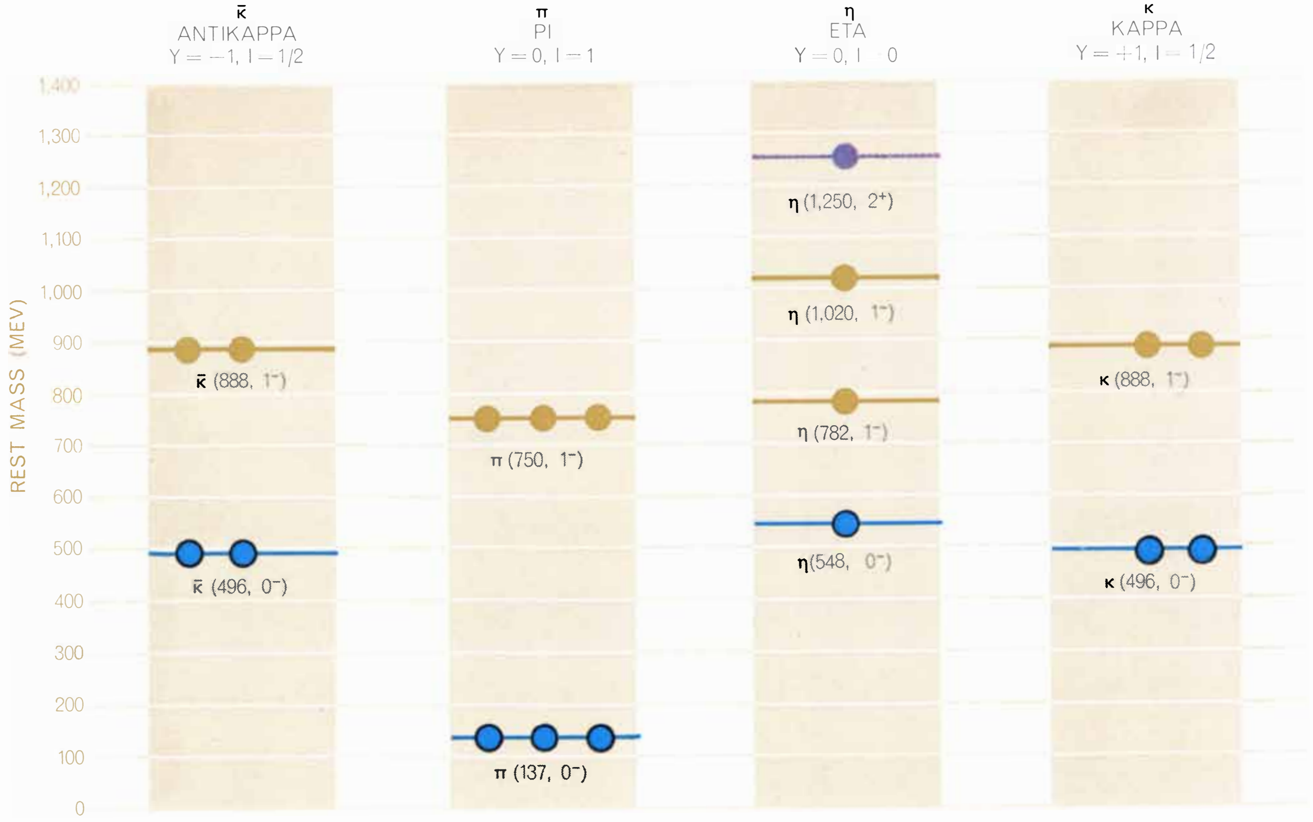
LETTER A = ATOMIC MASS, OR BARYON, NUMBER

PARENTHESES CONTAIN: (REST MASS IN MILLION ELECTRON VOLTS, SPIN ANGULAR MOMENTUM, PARITY)

STRONGLY INTERACTING with a new naming system. The in this chart include only those million electron volts (Mev) a (A) of − 1, 0 or + 1. All the pa to exist, with the exception of Ω(1,676, 3/2⁺) and its antipa existence has been predicted numbers in parentheses are mass assignments are averages



BARYON MULTIPLETS that have the same values of hypercharge (Y) and isotopic spin (I) are arranged in columns. Only six combinations of Y and I are known at present, each identified by an upper-case Greek letter. The particle symbols and color code are those presented on the preceding two pages. Particles above the break in the tan background are recurrences of low-lying states.



MESON MULTIPLETS with like values of Y and I are arranged in columns. Four combinations of Y and I are identified by lower-case Greek letters. No meson recurrences have yet been identified. The first predicted recurrence is a pi triplet at about 1,700 Mev.

bers, or physical quantities, that are conserved in strong interactions.

We shall next describe how these quantities are conserved when particles decay into different "channels," representing different modes of decay. This will lead to a description of "resonances," or unstable particles, which account for most of the proliferation among strongly interacting particles.

We shall then be ready to discuss two classification systems, or rules for the formation of groups, that have brought to light deep-seated family relations among strongly interacting particles. These rules have made it possible to predict the existence of still undiscovered particles, their approximate masses and certain other properties. One system is based on the concept of the "Regge trajectory"; the other is the "eightfold way."

Next we shall explain why the term "elementary" has fallen into disrepute for describing strongly interacting particles. There is growing evidence that all such particles can be regarded as composite structures. Finally we shall describe the "bootstrap" hypothesis, which may make it possible to explain mathematically the existence and properties of the strongly interacting particles. According to this hypothesis all these particles are dynamical structures in the sense that they represent a delicate balance of forces; indeed, they owe their existence to the same forces through which they mutually interact. In this view the neutron and proton would not be in any sense fundamental, as was formerly thought, but would merely be two low-lying states of strongly interacting matter, enjoying a status no different from that of the more recently discovered baryons and mesons and the nuclei of atoms heavier than those of hydrogen.

Forces and Reaction Times

In present-day physics the concepts of force and interaction are used interchangeably. The strong, or nuclear, force is the most powerful of the four basic interactions that, together with cosmology, account for all known natural phenomena. (Cosmology provides the stage on which the forces play their roles.) The strong interaction is limited to a short range: about 10^{-13} centimeter, which is about the diameter of a strongly interacting particle.

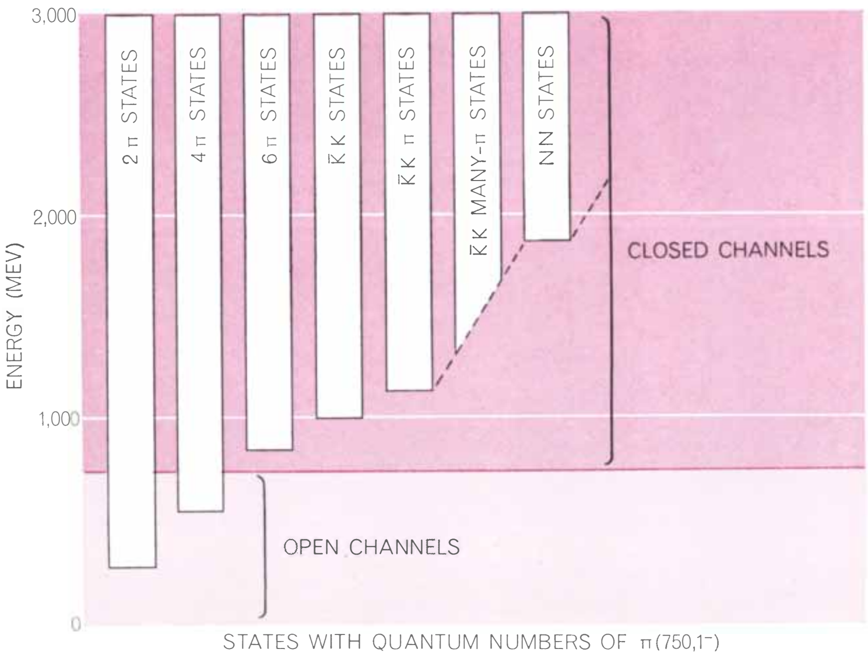
The next force, in order of strength, is the electromagnetic force, which is about 1 per cent as powerful as the strong force. Its strength decreases as the square of the distance between interacting particles, and its range is in principle unlimited. This force acts on all particles with an electric charge and involves the uncharged photon, which is the carrier of the electromagnetic-force field. The electromagnetic force binds electrons to the positively charged nucleus to form atoms, binds the atoms together to form molecules and thus in its manifold workings is responsible for all chemistry and biology.

Next in order, with only about a one-hundred-trillionth (10^{-14}) of the strength of the strong interaction, is the weak interaction. It also has a short range and cannot, as far as anyone knows, bind anything, but it governs the decay of many strongly interacting particles and is responsible for the decay of certain radioactive nuclei. It is most easily studied in the behavior of the four leptons, which do not respond to the strong force.

The fourth and weakest force is gravity, which has only about 10^{-39} of the strength of the strong interaction. It produces large-scale effects because it is always attractive and operates at long range. On the scale of atomic nuclei, however, its effects are undetectable.

Many particles are "coupled" to all four of these interactions. Take, for example, the proton. It is a strongly interacting particle, and since it is electrically charged it must also "feel" the electromagnetic force. It can be created by the beta decay of a neutron, a decay in which the neutron emits a negative electron and an antineutrino by a weak-interaction process; hence it must be involved in weak interactions. And like all other matter the proton is attracted by gravity. The least reactive particle is the neutrino, which is directly coupled only to the weak interaction and to gravitation. The neutrino shares with the other leptons a total immunity to the strong force.

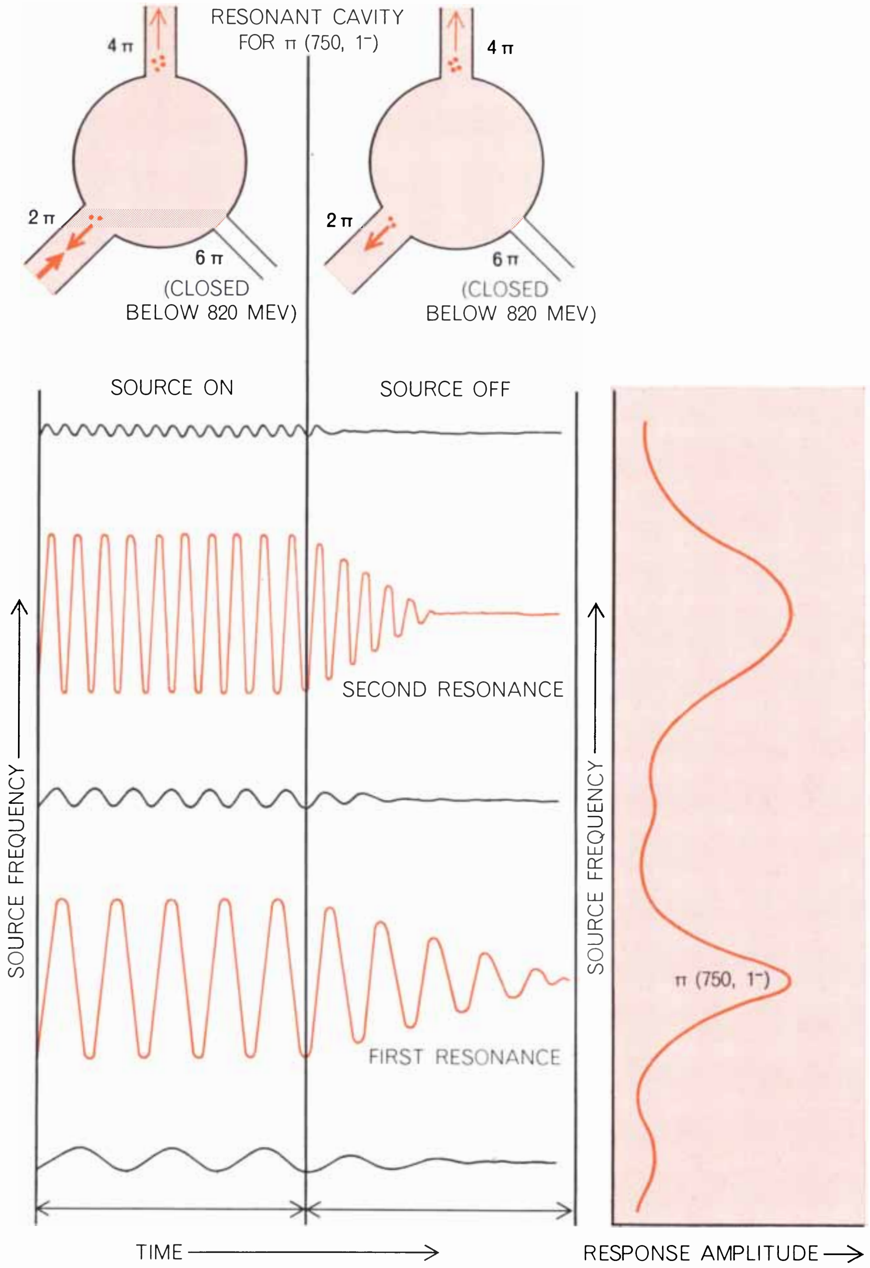
An important idea, not self-evident in the foregoing, is that the basic forces can do more than bind particles together. For instance, when two particles collide and go off in different directions (the phenomenon called scattering), an interaction is involved. If a particle is moving with enough energy before striking a particle at rest, a new particle can be created in the collision. The collision of a proton and a neutron can yield a proton, a neutron and a neutral pion, or it can yield two neutrons and a positive pion. The collision can also yield strongly interacting particles that are more massive than either of the colliding particles. This, in fact, is the process by which particle-accelerating machines have created the scores of new particles heavier than protons and neutrons. Thus the basic forces are



"COMMUNICATING CHANNELS" (*vertical bars*) **are nuclear states that possess all the same quantum numbers as a particular particle, in this case $\pi(750, 1^-)$. Channels into which it has sufficient energy to decay are "open" channels. Channels for which it lacks sufficient energy are "closed." The threshold energy for gaining access to a communicating channel is the sum of the rest masses (in Mev) of the various particles constituting the channel.**

interactions that can scatter, create, annihilate and transform particles.

The interactions of principal interest in high-energy physics take place when one of the particles in the interaction is traveling at nearly the speed of light, or more than 10^{10} centimeters per second. Since the size of a particle is typically about 10^{-13} centimeter, the minimum reaction time is less than 10^{-23} second for a particle moving at the speed of light. What we mean when we call the strong interaction "strong" is that even in that brief time the strong force is powerful enough to cause a reaction to take place. Electromagnetic reactions, being 100 times weaker than strong reactions, take around 100 times longer, or typically 10^{-21} second. Processes involving the weak interaction, which is 10^{-14} times weaker than the strong interaction, commonly take about 10^{-9} second.



RESONANT CAVITY analogy accounts for the appearance of unstable particles called resonances. The "cavity" for the $\pi(750, 1^-)$ meson is shown at top with an energy source present (*left*) and removed (*right*). Energy (*colored arrows*) can flow into the cavity through one channel and leave through one or more open channels. The 6π channel, however, is closed because access requires a higher frequency (that is, more energy) than $\pi(750, 1^-)$ possesses. The sinusoidal curves show that at certain frequencies the cavity resonates, and when the energy is turned off, the resonance can persist for several cycles. The first resonance corresponds to $\pi(750, 1^-)$ itself. A second resonance with the same quantum numbers could conceivably exist. The colored curve at right represents the amplitude of the resonant waves when the source amplitude is kept constant and the frequency is varied.

Conservation Laws

When one of the present authors (Gell-Mann) and E. P. Rosenbaum discussed particles in these pages not quite seven years ago [see "Elementary Particles," SCIENTIFIC AMERICAN, July, 1957], 30 well-established particles and antiparticles were singled out for attention. In this collection there were 16 baryons and antibaryons, seven mesons, six leptons and antileptons and the photon [*see illustration on page 75*]. At that time it was customary to classify as elementary not only the photon and the leptons but also all the baryons and mesons—the strongly interacting particles.

A distinction, which we now regard as unjustified, was drawn between these strongly interacting particles and the states of ordinary atomic nuclei containing two or more nucleons, which, of course, are also strongly interacting. These nuclei, such as the deuteron (the nucleus of heavy hydrogen) and the alpha particle (the nucleus of helium), had been classified as composite structures, made essentially of protons and neutrons, almost from the beginning of nuclear physics because of the small binding energies involved in them. This article will place little emphasis on such nuclei. We shall concentrate on the lighter particles, not because we believe them to be more elementary than their heavy brothers but because their status is still in doubt. If they are in fact composite dynamical structures, their binding energies are often enormous. Furthermore, if elementary particles do exist, they will certainly not include the obviously composite nuclei.

The chart on pages 76 and 77, which omits the photon and leptons, shows 82 particles and antiparticles, all of them strongly interacting, and the list has been arbitrarily limited to baryons and mesons with a rest mass less than 2,000 Mev. Most of the 82 particles belong to family groups that have acquired pet names comparable to, but usually less elegant than, the names given to those in the 1957 list. It would be unreasonable to expect the reader to master this specialized vocabulary, which reflects chiefly the confused state of high-energy physics a few years ago. We shall therefore introduce the reader to a new system of nomenclature that has developed quite recently and that provides a great deal of information about each particle. Although it may look forbidding at first sight, it is really no harder to master than the telephone company's all-digit dialing system.

The new classification scheme takes advantage of the fact that nature conserves many quantities (in addition to energy and momentum) and shows various symmetries (such as that between left and right). As a result groups of particles have similar properties, which, as we shall see, can be indicated by a common notation. There is a close relation between symmetries and conservation laws, and in a particular case one can refer either to a symmetry or to the associated conservation law, whichever is more convenient. The conserved quantity appears in quantum mechanics as a quantum number, which is often either an integer (such as 0, 1, 2, 3 and so on) or a half-integer (such as 1/2, 3/2, 5/2 and so on).

Some conservation laws appear to be universal: they are obeyed by all four basic interactions. This inviolable group includes the conservation of energy, of momentum, of angular momentum (the momentum associated with rotation) and of electric charge. Another exact conservation law is best described as a kind of mirror-image symmetry. It is the symmetry between particles and antiparticles, in which whatever is left-handed for one is right-handed for the other. For each particle there is an antiparticle with the same mass and lifetime but with some properties, such as electric charge, reversed. Some neutral particles, such as the photon and the neutral pion, are their own antiparticles.

In the new system for naming strongly interacting particles we shall make use of five quantities, each indicated by a letter symbol, that are conserved by the strong interactions but not necessarily by the electromagnetic or weak interactions. These five quantities are: atomic mass number (*A*), hypercharge (*Y*), isotopic spin (*I*), spin angular momentum (*J*) and parity (*P*). The chart on the next page should help the reader to keep these five quantum numbers in mind as we discuss them in more detail. Also included in the chart are two other quantities that are conserved by strong interactions but that are not essential to the naming system: electric charge (*Q*) and a quantity called *G* that has only two values, +1 and −1, and can be assigned only to mesons that have a hypercharge of 0.

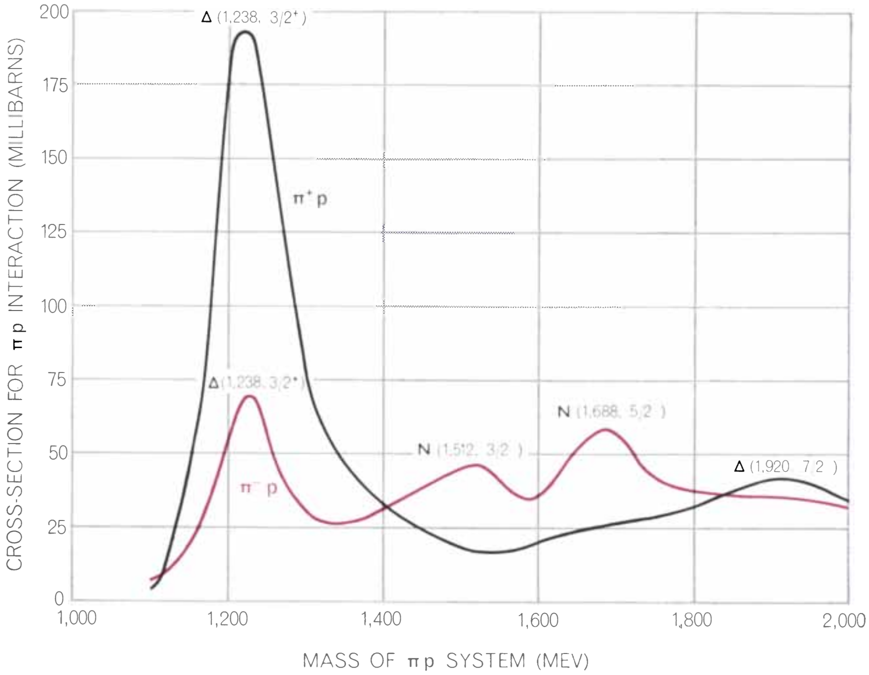
The first three quantum numbers—*A*, *Y* and *I*—provide the basis of the naming system. What these three numbers do, in effect, is to describe the geometric pattern of the particles as they are arranged in the chart on pages 76 and 77. There it will be seen that mesons and baryons occur in "charge multiplets," or families of states differing only in their electric charge. The number of particles and their charges occur in different patterns: singlets, doublets, triplets and quadruplets. Only 10 different patterns are known or predicted at present, and each pattern represents a different set of values for *A*, *Y* and *I*. As we shall explain, each of the 10 patterns is identified by a different Greek letter.

Now we shall describe the physical significance of *A*, *Y*, *I*, *J* and *P*, but for convenience we shall discuss them in a slightly different order to emphasize certain relations among them. *A* is simply the long-familiar atomic mass number used to describe atomic nuclei. It is also known as baryon number. Like electric charge, *A* can be 0, ±1, ±2, ±3 and so on. For uranium 235, *A* is 235, indicating that the nucleus of this isotope contains 235 neutrons and protons, for each of which *A* equals 1. Neutrons and protons are baryons and, by definition, so are all other particles with an *A* of 1. Particles with an *A* of −1 are antibaryons. Mesons have an *A* of 0 (as do the leptons and the photon). The law of baryon conservation states that the total value of *A*, like electric charge, can never change in a reaction. Baryons cannot be created or destroyed, except when a baryon-antibaryon pair annihilate each other or are created together.

The second conserved quantity is *J*, or spin angular momentum, which measures how fast a particle rotates about its axis. It is a fundamental feature of quantum theory that a particle can have a spin of only integral or half-integral multiples of Planck's constant. (This constant, $\hbar$, relates the energy of a quantum of radiation to its wavelength: energy equals 2π times frequency times $\hbar$.) For baryons *J* is always half-integral (that is, half an odd integer, such as 1/2, 3/2, 5/2 and so on) and for mesons *J* is always integral (that is, 0, 1, 2 and so on).

The third conserved quantity, closely associated with *J*, is *P*, or intrinsic parity. Parity is conserved when nature does not distinguish between left and right. Because such symmetry is observed in strong interactions, quantum mechanics tells us that an intrinsic parity value of +1 or −1 can be assigned to each strongly interacting particle. In the case of weak interactions, however, nature does distinguish between left and right, and the symmetry is violated.

The bookkeeping on parity is not quite so simple as that for electric charge and baryon number; the intrinsic parity values on each side of an equation are not



FIRST RESONANCE, the unstable particle called Δ(1,238, 3/2+), was discovered by Enrico Fermi and his colleagues in 1952. The resonance appears when protons are bombarded with high-energy pions. When the interaction "cross section" is plotted against the effective mass of the pion-proton system, a peak is found at around 1,238 Mev. The peak is much larger for the π^+p interaction than for the π^-p interaction. Other resonances occur at 1,512, 1,688 and 1,920 Mev, each peak corresponding to an unstable particle.

necessarily the same. The reason is that the total parity is affected by spin angular momentum as well as by intrinsic parity. The close connection between parity and spin angular momentum makes it convenient to write the spin angular momentum quantum number J and the intrinsic parity P next to each other in describing each particle. For the proton, for example, J equals 1/2 and P equals $+1$, which is shortened to J^P equals $1/2^+$. For the pion J equals 0 and P is -1, so that one writes J^P equals 0^-. (The system of bookkeeping for J is actually quite complicated in quantum mechanics, but the details need not concern us here.)

The fourth quantity conserved in strong interactions is I, or isotopic spin. This quantum number has nothing to do with spin or angular momentum, except that its peculiar quantum-mechanical bookkeeping is similar to that for J. The concept of isotopic spin was originally introduced into quantum mechanics to accommodate the fact that the nucleon exists in two charge states: one positively charged (the proton) and the other neutral (the neutron). As far as strong interactions are concerned, these two states behave alike; they are related to each other by the symmetry of isotopic spin. Moreover, if the symmetry were observed by the electromagnetic interaction, the proton and the neutron would have the same mass. Precisely because isotopic-spin symmetry is violated by the electromagnetic interaction the neutron is 1.3 Mev (or .14 per cent) more massive than the proton.

A set of particles or particle states (we use the terms interchangeably) related to each other by isotopic-spin symmetry is a charge multiplet and is given a single name. Thus the nucleon doublet consists of the two charge states, positive and negative. The pion triplet consists of negative, neutral and positive charge states. The number of different charge states in a multiplet, or its "multiplicity" (M), is directly related to the isotopic-spin quantum number I by the equation $M = 2I + 1$. For the nucleon M equals 2 and I equals 1/2; for the pion M equals 3 and I equals 1.

The fifth conserved quantity goes by any of three names: average charge ($\bar{Q}$), hypercharge (Y) or strangeness (S), which are related to each other in a simple way. Average charge is just what its name implies: the average of the electric charges in a multiplet. Hence for the nucleon it is 1/2 (0 plus 1 divided by 2); for the pion it is 0. Hypercharge is defined as twice the average charge (Y equals $2\bar{Q}$) merely to make it an integral number. And strangeness is hypercharge minus the baryon number (S equals Y minus A). It is clear that the three quantities are in effect interchangeable.

The concept of strangeness and its conservation is only 11 years old. In the early 1950's certain particles such as the K, the sigma and the xi were being observed for the first time, and because of their unusual behavior they were referred to as "strange particles." Most of them have relatively long lifetimes, which indicates that they decay by the weak interaction rather than by the electromagnetic or strong interaction. On the other hand, they are readily produced in high-energy collisions of "ordinary" particles (pions and nucleons), which proves that the strange particles too are strongly interacting. When invariable behavior patterns of this sort are observed, the

CONSERVED QUANTITY	SYMBOL	OBSERVED VALUES	DESCRIPTION	EXAMPLES proton	negative pion
ELECTRIC CHARGE	Q	0, ±1, ±2, ±3 . . .	Represents the number of electric-charge units carried by a particle, or atomic nucleus, in units of the positive charge on the proton. Charge multiplets, such as the neutron-proton doublet or the pion triplet, can be assigned an average charge, $\bar{Q}$.	$Q=+1$ $\bar{Q}=+1/2$	$Q=-1$ $\bar{Q}=0$
ATOMIC MASS NUMBER, OR BARYON NUMBER	A	0, ±1, ±2, ±3 . . .	Represents the familiar atomic mass number long used for nuclei. For uranium 235, A = 235. For baryons, A = +1; for antibaryons, A = −1; for mesons, A = 0.	A = +1	A = 0
HYPERCHARGE (Related to average charge, $\bar{Q}$, and to strangeness, S)	Y	−2, −1, 0, +1	Defined as twice the average charge, $\bar{Q}$, of a multiplet. Strangeness, S, is hypercharge minus the atomic mass number (S = Y − A).	Y = +1 S = 0	Y = 0 S = 0
ISOTOPIC SPIN (Related to multiplicity, M)	I	0, 1/2, 1, 3/2	Groups nuclear states into multiplets whose members differ only in electric charge. The number of charge states, or multiplicity, M, is related to I by the equation M = 2I + 1.	I = 1/2 M = 2	I = 1 M = 3
SPIN ANGULAR MOMENTUM	J	1/2, 3/2, 5/2 . . . 0, 1, 2, 3 . . .	Indicates how fast a particle rotates about its axis, expressed in units of Planck's constant, $\hbar$.	J = 1/2	J = 0
PARITY	P	−1, +1	An intrinsic property related to left-right symmetry.	P = +1	P = −1
G	G	−1, +1	An intrinsic property found only in mesons with zero hypercharge.	not defined	G = −1

CHART OF QUANTUM NUMBERS shows seven quantities conserved by the strong interaction but not necessarily by the electromagnetic or weak interaction. The three quantities in color (A, Y, I) are easily established by experiment and provide the basis for assigning a family name to each particle. Only 10 combinations of A, Y and I are now known, each represented by a Greek letter.

physicist suspects that a conservation law (or symmetry) is at work. One of the authors of this article (Gell-Mann) and the Japanese physicist Kazuhiko Nishijima independently proposed that a previously unsuspected quantity (strangeness, or hypercharge) is conserved in strong and electromagnetic interactions but violated by weak interactions. The hypothesis made it possible to predict the existence and general properties of several strange particles before they were discovered.

The New Nomenclature

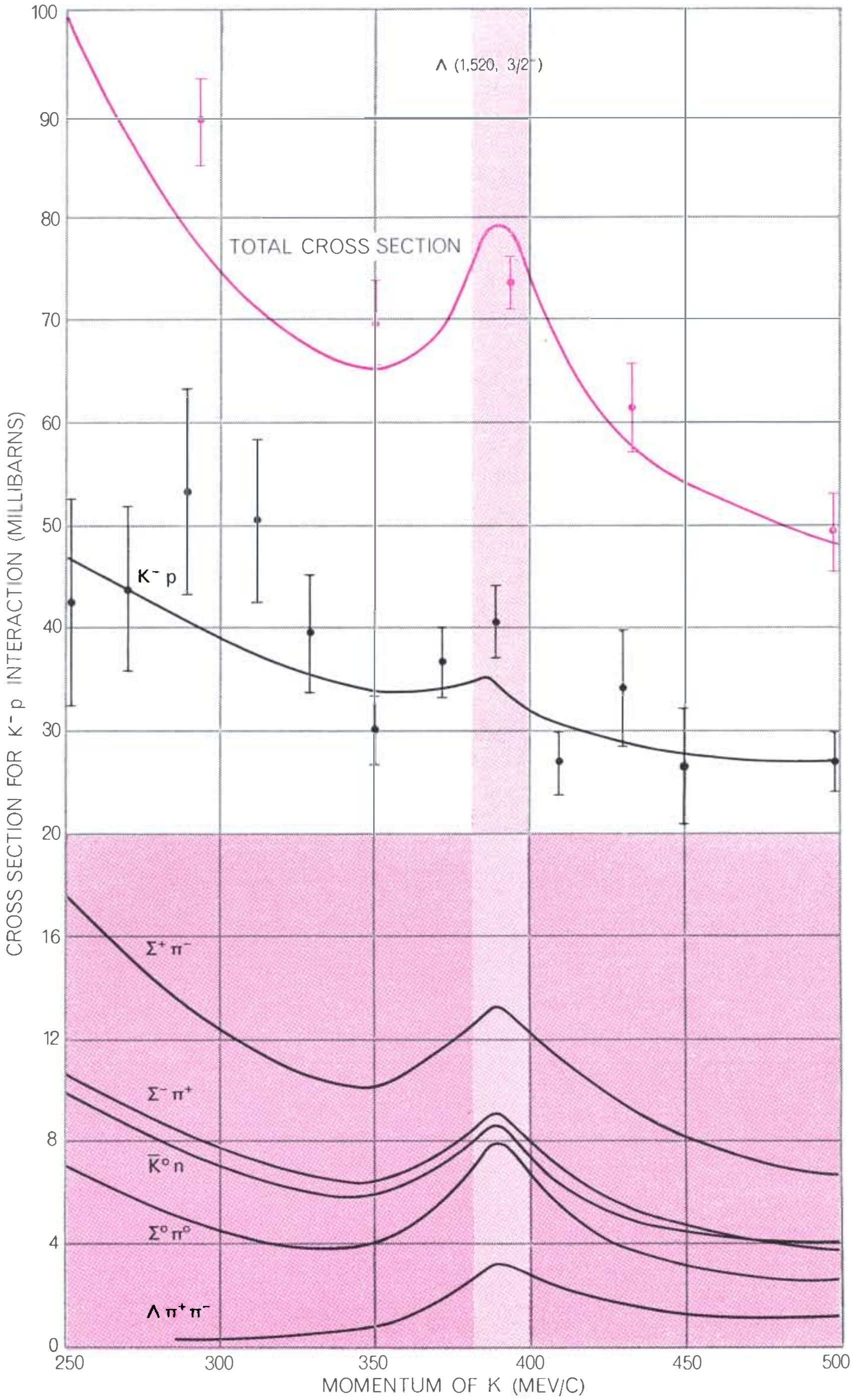
We are now ready to describe how the five quantum numbers can provide the basis for a new naming system. By appropriate selection of three of the five quantum numbers we can indicate immediately whether a strongly interacting particle is a baryon or a meson, how many members it has in its immediate family (that is, its multiplicity) and what its degree of strangeness is. The three quantum numbers that provide this information are the atomic mass, or baryon, number A, the hypercharge Y and the isotopic spin I. (It will be recalled that Y is directly related to strangeness and I to multiplicity.)

Now, partly as a mnemonic aid and partly out of respect for the old pet names, we shall employ a letter symbol to indicate various combinations of A, Y and I. To designate the known mesons, particles for which A is 0, it is sufficient to use four lower-case Greek letters: η (eta), π (pi), κ (kappa) and $\bar{\kappa}$ (antikappa, or kappa bar). The chart at the bottom of the next page shows the Y and I values for each symbol. Even though the multiplicity M can be found simply by doubling I and adding 1, it is shown separately for easy reference.

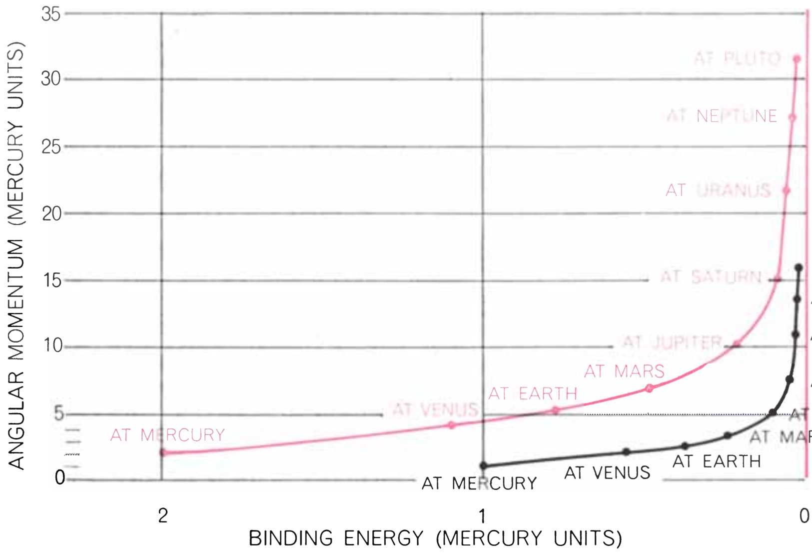
To designate baryons, for which A is 1, we will use the following upper-case Greek letters: Λ (lambda), Σ (sigma), N (which stands for the nucleon and is pronounced "en," not "nu"), Ξ (xi), Ω (omega) and Δ (delta). The values of Y, I and M for each symbol are also shown at the bottom of the next page.

These 10 symbols encompass all the kinds of meson and baryon states that are known at the present time. In other words, any of the 82 particles in the chart on pages 76 and 77 can be designated by one of these 10 symbols. The difference between the old naming system and the new one should now be apparent. In the old system, shown in the chart on page 75, the symbol π, for example, represented only a single family of three particles with a rest mass of 137 Mev. In the new system π represents both that group and a new group of three, with identical A, Y and I but with a rest mass of 750 Mev. Similarly, in the old system N stood only for the nucleon doublet with a mass of 939 Mev. In the new system N stands for the nucleon and for two higher energy states, also doublets, one with a mass of 1,512 Mev and one with a mass of 1,688 Mev. Thus the old particle names now stand for classes of particles with the same A, Y and I.

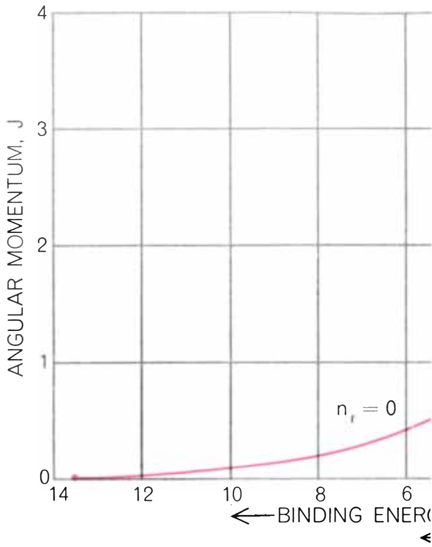
Various members of a class can be



MULTIPLE DECAY MODES of Λ(1,520, 3/2−) show that the baryon Λ is connected to six open channels. The Λ is created when K− mesons [κ(496)] are scattered on protons. The total interaction cross section shows a peak corresponding to the formation of Λ(1,520, 3/2−), which speedily decays into one of the six channels indicated. Thus the curve labeled K−p represents the over-all reaction: K−p → Λ ↔ K−p. Thousands of bubble-chamber "events" *(see cover)* supplied data for the curves. Data points are given only for the top two.



"REGGE TRAJECTORIES," an important concept for predicting recurrences, can be explained with a spaceship analogy. If one-ton spaceships were placed in circular orbits around the sun at the distance of each of the nine planets, the ships would have the binding energies and angular momenta indicated. The black curve drawn through these values is a Regge trajectory. The colored curve is a Regge trajectory for a two-ton spaceship.



TRAJECTORIES FOR HYDROGEN resemble those for a spaceship. The hydrogen atom, made up of an electron "circling" a proton, can exist in various states of excitation. For each value of a certain quantum

distinguished by writing the mass value in parentheses after the name, for example π(137) or π(750); or by writing the angular momentum *J* and the parity *P* in parentheses, for example $\pi(0^-)$ or $\pi(1^-)$. Or, if desired, mass, *J* and *P* can all be shown: $\pi(137, 0^-)$ or $\pi(750, 1^-)$. In the following discussion an unadorned symbol will refer to the lowest mass state in the class. The new classification system is exhibited in the baryon and meson charts on page 78.

Particle Stability

We mentioned earlier that particles can decay in one of three ways: via the strong, the electromagnetic or the weak interaction. A few particles (the photon, the two neutrinos, the electron and the proton) are absolutely stable provided that they do not come into contact with their antiparticles, whereupon they are annihilated. Particles that decay through the electromagnetic or weak interaction are said to be metastable. Those that decay through the strong interaction are called unstable and have very short lifetimes, typically a few times 10^{-23} second. This is still a considerable length of time, however, compared with less than 10^{-23} second, which is the characteristic time required for a collision between high-speed particles.

Unstable particles are those with enough energy to decay into two or more strongly interacting particles without violating any of the conservation laws respected by the strong interaction. Some unstable particles have only one possible decay mode; others have more than one. As an example of the former, Ξ(1,530) decays only into Ξ and π. On the other hand, Λ(1,520) can decay into Σ and π, into N and $\bar{\kappa}$ or into Λ and two π's.

How can the existence of several decay modes be explained? This can be answered by introducing the concept of "communicating states." A nuclear state can be either a single particle or a combination of two or more particles. We have seen that each particle has definite values of the conserved quantum numbers *A*, *Y*, *I*, *J*, *P* and, where applicable, *G*. The strong interaction allows transitions, or communication, only among nuclear states with the same values for all the conserved quantum numbers.

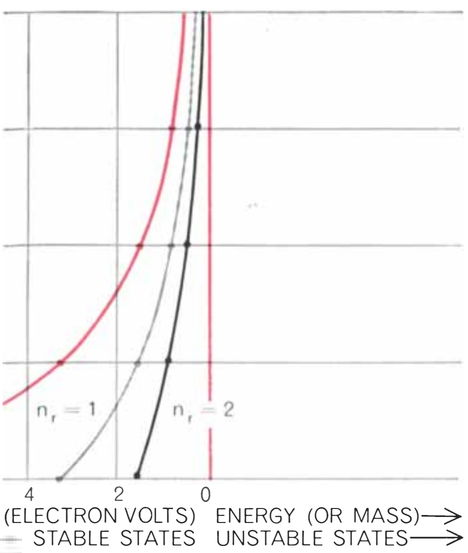
Now, one can write down many nuclear states, consisting of two or more particles, that have in the aggregate the same set of quantum numbers as any particular unstable particle. For decay to take place, however, the unstable particle must have a rest mass at least equal to the threshold energy (that is, the sum of the rest masses) of the particles into which it might conceivably decay. In other words, energy must be conserved. The various states into which an unstable particle has sufficient energy to decay are called open channels. Communicating states with threshold energies greater than that available to the unstable particle are called closed channels; decay into them is allowed by everything *but* conservation of energy. A schematic representation of some of the channels that communicate with $\pi(750, 1^-)$ is shown on page 79.

This leads us to the concept of "resonance," the term originally applied to unstable particles. The first of these was discovered in 1952 at the University of Chicago by Enrico Fermi and his colleagues. At the time no one suspected that a deluge was to follow.

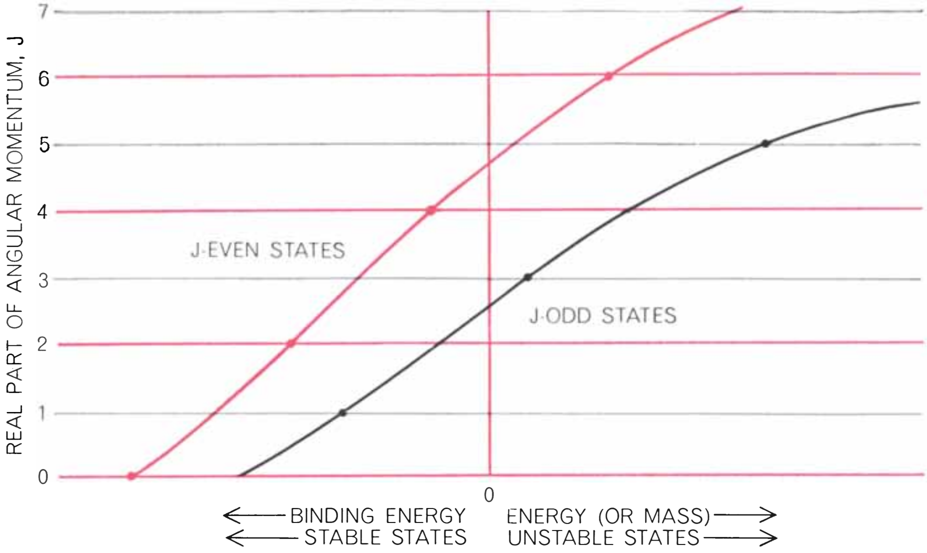
MESONS	Y	I	*M*
η	0	0	*1*
π	0	1	*3*
κ	+1	1/2	*2*
$\bar{\kappa}$	−1	1/2	*2*

BARYONS	Y	I	*M*
Λ	0	0	*1*
Σ	0	1	*3*
N	+1	1/2	*2*
Ξ	−1	1/2	*2*
Ω	−2	0	*1*
Δ	+1	3/2	*4*

SYMBOLS FOR MESONS AND BARYONS are Greek letters. For mesons atomic mass number *A* is 0; for baryons it is 1. The 10 letters identify the 10 known combinations of mass number (*A*), hypercharge (*Y*) and isotopic spin (*I*). Multiplicity (*M*) is related to *I*.



number (n_r) the binding energies of the hydrogen states decrease with increasing values of angular momentum (*J*). Smooth curves drawn through these states (each a different "particle") are Regge trajectories.



TRAJECTORIES FOR STRONGLY INTERACTING PARTICLES resemble those at left except that they include unstable states. An intersection with *J* in the stable region indicates the existence of a stable or metastable particle. Intersections in the unstable region indicate an unstable particle. Trajectories connect particle states separated by two full units of *J*. Lowest state is an "occurrence"; higher states are "Regge recurrences."

In the 1952 experiments pions from the University of Chicago cyclotron were directed at protons (in liquid hydrogen) and the scattering cross section was measured for different energies of the pion beam. Scattering refers to the change of direction when two particles collide; the scattering cross section is the probability that scattering will occur. When the probability is large, the two particles act as if they were big, with a large cross section.

For each setting of the pion beam the "effective" mass of the pion-proton system is calculated. The effective mass is the sum of the rest masses and the kinetic energies of all the particles in a system, as viewed from the system's center of mass. When the effective mass is plotted along one co-ordinate of a graph and the scattering cross section along the other, it is found that the cross section peaks sharply when the system has an effective mass of about 1,238 Mev. It is through this peak that the resonance was detected. We shall discuss below the connection between the peak and the resonance, or unstable particle, that is called Δ(1,238) in our new notation.

The University of Chicago cyclotron could not create pion-proton systems with an effective mass of much more than 1,300 Mev. Subsequently, with more powerful accelerators, it was found that pion-proton scattering produces a whole series of resonances. The illustration on page 81 shows two resonances created when positive pions are scattered by protons and, in a separate curve, four resonances created when negative pions are scattered by protons. The first two resonances are Δ(1,238, $3/2^+$) and Δ(1,920, 7/2). The same two should also show up in negative pion scattering, but in the actual experimental curve for the negative pion the upper one, Δ(1,920, 7/2), is hardly observable. We do see, however, two other resonances, N(1,512, 3/2) and N(1,688, 5/2), that cannot contribute to the scattering of positive pions by protons. (A space in the parentheses following the half-integer value of *J* indicates that the parity of the particle has not yet been established.)

Although Δ(1,238) decays mainly into one pion and a nucleon, the higher resonances can also decay into two or more pions and a nucleon. Most resonances can decay in more than one way; that is, they can communicate with several open channels [*see illustration on page 83*].

To explain how an unstable particle can communicate with several open channels we have found it helpful to draw an analogy between the behavior of unstable particles and the behavior of resonant cavities such as organ pipes and electromagnetic cavities. Cavities of the latter sort (such as the magnetron tube employed in radar) are used in electronics to create intense electromagnetic waves of a desired frequency, which is a resonant frequency of the cavity. Each cavity has a characteristic "lifetime": the time required for the electromagnetic radiation to leak out.

In quantum mechanics, particles and waves are complementary concepts, and the amount of energy associated with a particle, or nuclear state, can be expressed as an equivalent frequency. In other words, energy is proportional to frequency. The fact that the Δ particle appears when a pion is scattered by a proton at or near a certain energy —the resonance energy—is equivalent to saying that the particle appears at a certain frequency. Thus a resonance energy in particle physics can be compared to the resonance frequency of an acoustic or electromagnetic cavity. What is the "cavity" in particle physics? It is an imaginary structure: one cavity, each with its own special properties, for each set of values of the quantum numbers conserved in strong interactions.

The analogy between unstable particles and the resonant modes of electromagnetic cavities can be carried further. To the electromagnetic cavity one can attach the long pipes known as wave guides, which have the property of efficiently transmitting electromagnetic waves of high frequency but not those of low frequency. When the electromagnetic wavelength is slightly larger than the dimensions of the wave guide, the guide refuses to transmit. In this sense the wave guide acts like a particle channel that is open only above its characteristic threshold energy. If a cavity has attached to it several wave guides of different sizes, high-frequency radiation can flow into the cavity through one guide and flow out through the same or different guides.

By analogy energy can flow into a nuclear interaction through one channel and pass out through one or more open channels. As the energy (frequency) is increased from low values, the channels open up one by one and new nuclear reactions become possible, with energy going out through any of the open channels. Now, as the frequency is increased, suppose it passes through a resonance frequency of the nuclear cavity. At this point it becomes easier for the cavity to absorb and reradiate energy. The resonance appears as a peak in the scattering cross section of a nuclear reaction. In other words, a resonant mode of the cavity corresponds to an unstable particle, such as Δ or π(750).

Just as an electromagnetic cavity that is near resonance holds on to electromagnetic energy for a long time, so the unstable particle typically takes somewhat more than the characteristic time of less than 10^{-23} second to decay. If energy is fed into the cavity through one pipe, stays in the cavity for a while because of resonance and comes out again through the original pipe, that corresponds to a scattering collision between two π(137) particles that produce the unstable particle π(750), which finally decays again into the original particles. Alternatively, the energy can emerge through another pipe, which corresponds to the case in which π(750) decays into four π(137) particles. These, of course, are only two of many examples. The cavity and wave guide analogies are illustrated on page 80.

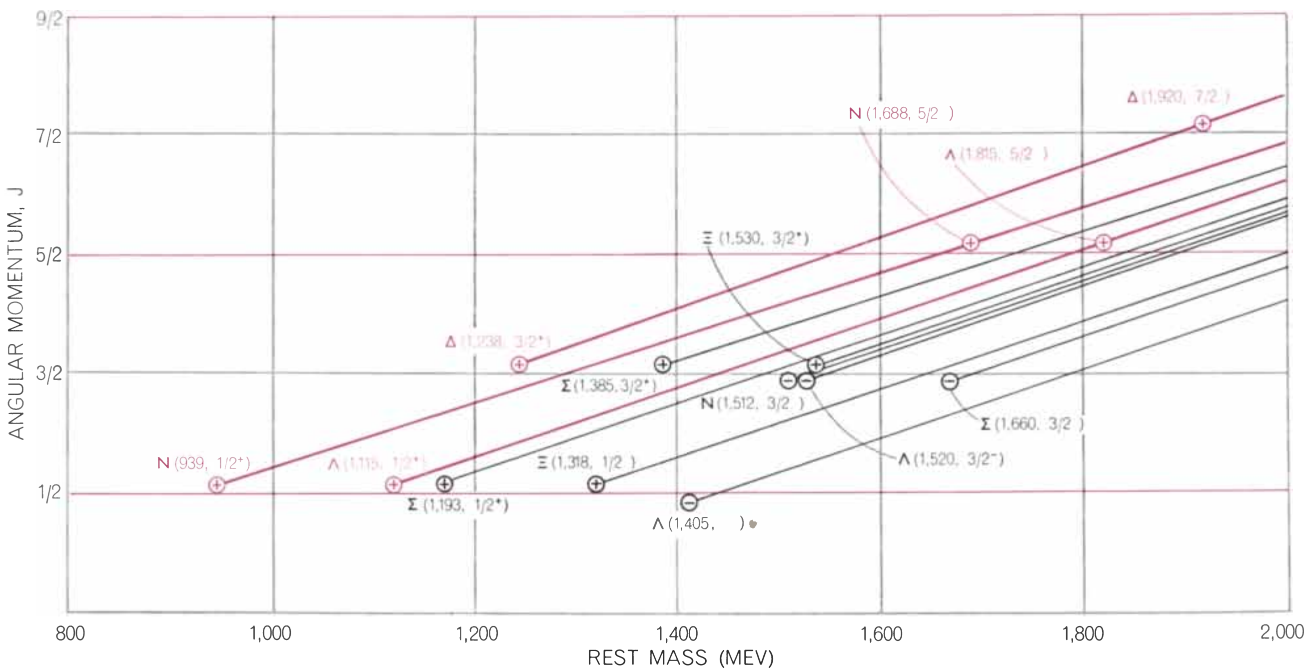
One can use the wave guide analogy to describe not only unstable particles but also stable ones. A stable particle is merely one that has such a low mass that all the communicating channels are closed. Therefore it is a "bound" state rather than a scattering resonance. For an electromagnetic cavity this condition would correspond to a resonant mode whose frequency is below the threshold frequency of all the wave guide outlets. If radiation could be put into the cavity in such a mode, it could not leak out. Of course, an actual cavity would eventually lose radiation by leakage into and through its walls. Such leakage corresponds to the decay of metastable particles via the weak and electromagnetic reactions. An absolutely stable particle really does live forever.

The reader who is unfamiliar with the phenomenon of resonance in electromagnetic cavities may be wondering if we have simplified his task by introducing the electromagnetic analogy. Would it not be just as easy to explain resonances in particle physics directly? Possibly so. But by drawing attention to similar behavior in two apparently different fields we hope we have illustrated a unity in physics that may make particle behavior seem less esoteric. The more basic value of the analogy, however, is that it has helped theorists to understand some deeper points in particle resonances than we have been able to talk about here.

Regge Trajectories

As the strongly interacting particles proliferated, physicists sought to find patterns that would show relations among them. In particular they tried to find classification systems that might predict new particles on the basis of those already known. The first concept to prove useful in this respect developed from an idea introduced into particle physics in 1959 by the Italian physicist Tullio Regge. The concept already had counterparts throughout quantum physics, notably in the study of atomic- and nuclear-energy levels.

It had been observed that as particles increase in mass they frequently (but not invariably) exhibit a higher value of spin angular momentum *J*. Regge pointed out the existence, in many important cases, of a mathematical relation between the value of *J* and particle mass. He showed that certain properties of particles can be regarded



REGGE TRAJECTORIES FOR BARYONS are shown for 14 well-established baryons with mass less than 2,000 Mev. Slanting colored lines connect three occurrences with their Regge recurrences. For baryons spin angular momentum (*J*) is half-integral (1/2, 3/2, 5/2 and so on). Recurrences must have 2, 4, 6 and so on more units of spin than their ground states (occurrences) of lowest mass. Spins for Λ(1,815, 5/2) and Δ(1,920, 7/2) are uncertain, but they probably satisfy this requirement. Slanting black lines show the probable Regge trajectories for other baryons. Circled symbols indicate parity; where not yet established, it has been guessed.

as "smooth" mathematical functions of J, that is, functions that vary continuously as J varies. But since in quantum mechanics J can have only integral and half-integral values, the functions have direct physical meaning only for those permitted values. The smooth mathematical curve that gives the physical mass for different values of J is called a "Regge trajectory."

A spaceship analogy may help to clarify the concept of the Regge trajectory. Suppose in the nearly circular orbit occupied by each of the sun's nine planets one were to place a one-ton spacecraft. These craft circle the sun as if they were miniature planets. The nearer a craft is to the sun, the more strongly it "feels" the sun's gravitational force and the more strongly it is bound. This binding energy, therefore, is highest for the craft in Mercury's orbit and least for that in Pluto's orbit. (The binding energy is just that amount needed to release the craft from the sun's attractive force.)

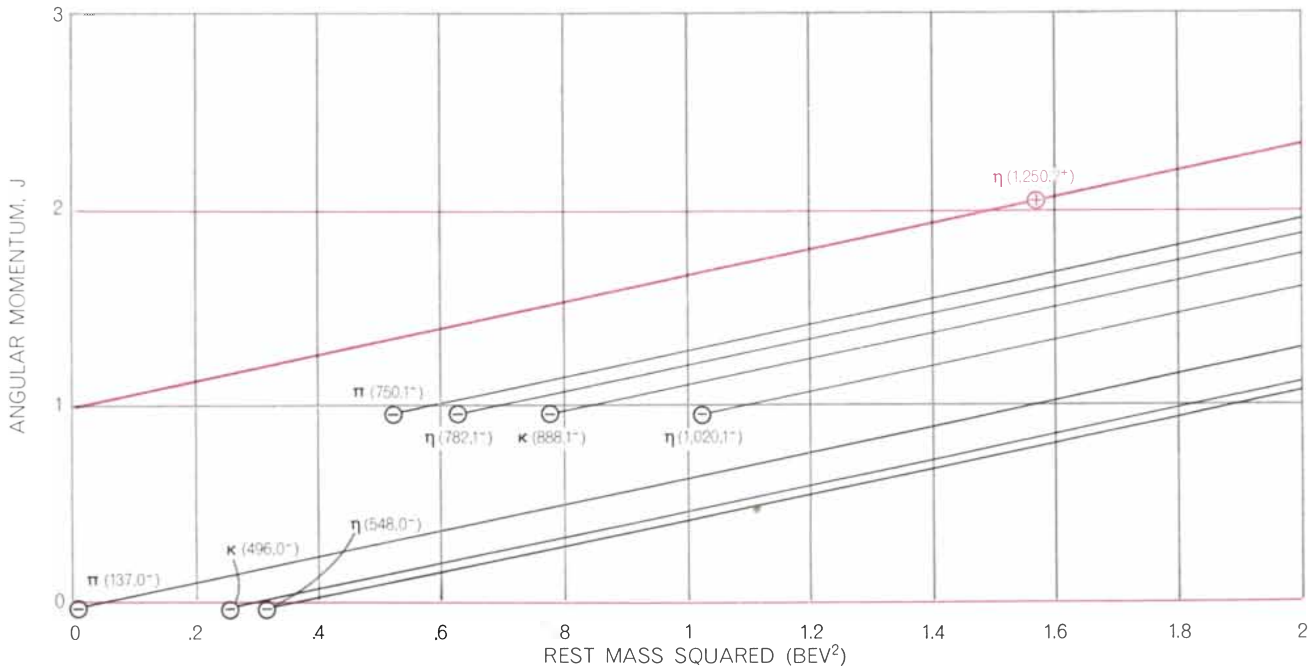
Each craft can be assigned another quantity that also varies with its distance from the sun: angular momentum. It frequently happens in physics that, other things being equal, the greater the binding energy, the smaller the angular momentum. In our example this means that angular momentum increases with the distance from the sun. One can now draw a graph for the nine spacecraft in which angular momentum is plotted on the vertical axis and binding energy on the horizontal axis [*see illustration at top left on page 84*]. The curve drawn through the plotted points is analogous to a Regge trajectory.

Now, suppose quantum mechanics were to have a controlling effect on the macroscopic scale of spacecraft and solar orbits. Suppose, that is, the angular momentum of the spacecraft in Mercury's orbit represented an elementary quantum of spin. If such were the case, a one-ton craft would be allowed to occupy only those orbits in which the angular momenta (expressed in Mercury units) assumed integral values. This is equivalent to saying that a one-ton craft in a circular orbit could exist only at certain energy levels. The Regge trajectory for the spaceship would then be physical only at these points. Another Regge trajectory could be drawn for a two-ton spacecraft. In any given circular orbit its binding energy and angular momentum would be twice that of a one-ton spacecraft.

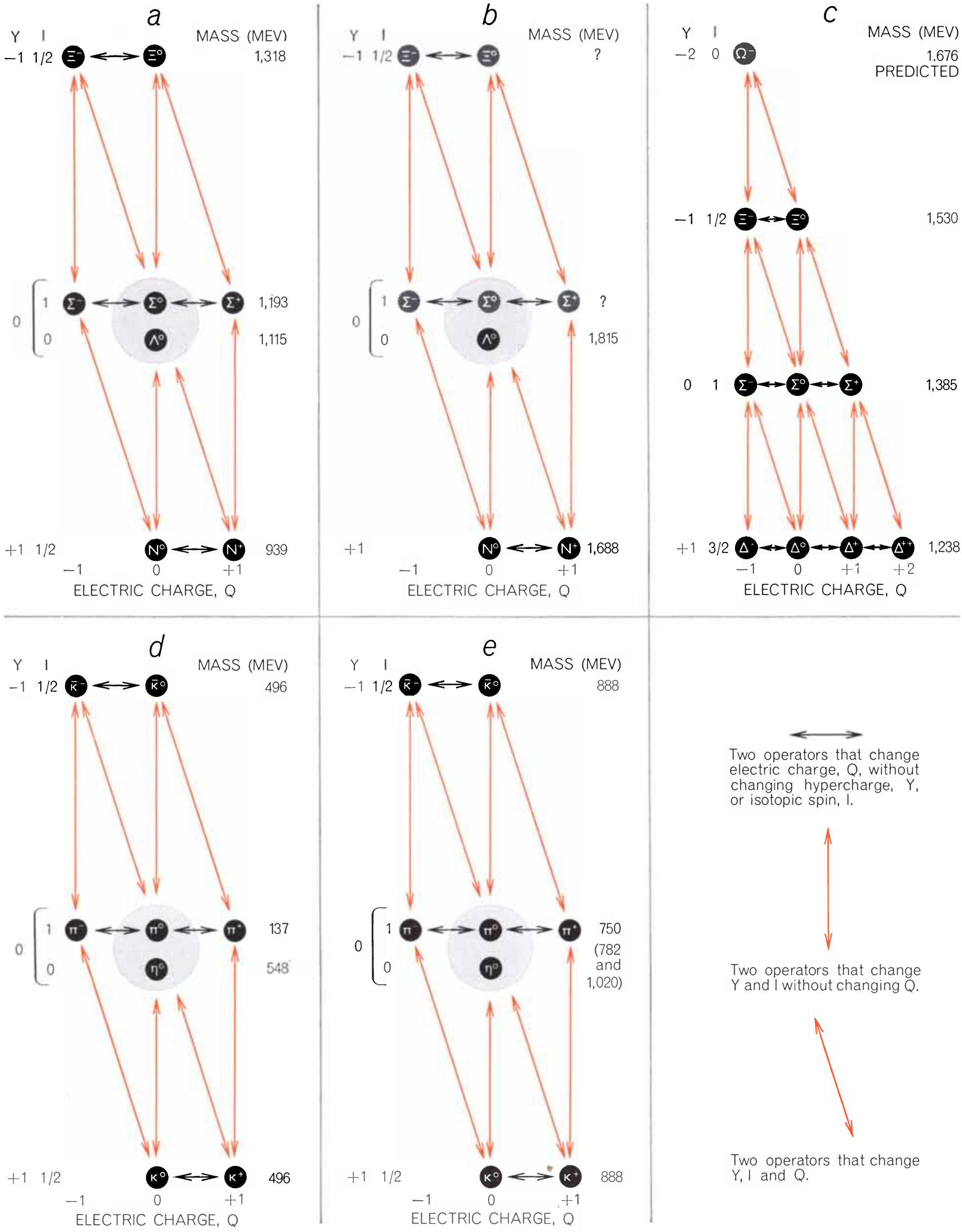
Although it was not used by physicists until recently, the notion of a Regge trajectory applies to problems long familiar in atomic physics. It is well known, for example, that the electron-proton system constituting the hydrogen atom can exist in various states of excitation. The electron can occupy various orbits around the proton, just as the spaceship could occupy many orbits around the sun. In the case of the electron, of course, the quantization of the orbits is very conspicuous. When the value of a certain quantum number, n_r (a number characterizing the energy of motion in a radial direction), is held fixed, the binding energies of the various hydrogen states decrease with increasing values of the angular momentum J. If a smooth curve is drawn through the permitted values of J, one obtains a Regge trajectory similar to that connecting the spacecraft in different orbits [*see middle illustration at top of pages 84 and 85*]. For each value of n_r in the hydrogen atom there is a different trajectory, just as there is for each spacecraft of different mass.

In the case of the hydrogen atom the intersection of a Regge trajectory with a permitted value of J (0, 1, 2 and so on) corresponds to the occurrence of a bound state. From an experimental standpoint each of these occurrences is a different "particle" with a different mass. The series of occurrences is brought to an end when the excitation energy becomes so great that the electron is dissociated from the proton. This energy limit divides stable states from unstable states.

Just as Regge trajectories can be



REGGE TRAJECTORIES FOR MESONS are shown for eight well-established particles. They are all in the ground state; no recurrences have yet been identified. It can be shown that the highest η trajectory (that is, a trajectory with a Y and I of 0) should have an unreal intersection at J of 1 and mass 0. A colored line drawn through that point and $\eta(1{,}250, 2^+)$ indicates the probable slope of Regge trajectories for mesons. The parallel black lines for other trajectories are hypothetical. Their intersections with a J of 2 or 3 predict where Regge recurrences are likely to be found. The lowest-lying recurrence should be a $\pi(2^-)$ of about 1,700 Mev.



"EIGHTFOLD WAY" invokes a new system of symmetries to group multiplets of particles into "supermultiplets." The term "eightfold" refers to a special algebra showing relations among eight things, in this case eight conserved quantities. The new system of symmetries (*colored arrows*) connects different values of hypercharge (*Y*) and isotopic spin (*I*) in the same way that isotopic-spin symmetry (*black arrows*) connects different values of electric charge. Four of the diagrams (*a*, *b*, *d*, *e*) show supermultiplets with eight members; another group (*c*) contains 10 members. Several new particles are predicted by the eightfold way, notably $\Omega(1{,}676, 3/2^+)$, which appears in *c*. Note that the η meson in *e* is given two mass values, which leads to the "identity crisis" described in the text.

drawn for the gravitational force (spaceship example) and the electromagnetic force (hydrogen-atom example), trajectories can be drawn for the strong force governing strongly interacting particles. In this case the trajectories do not terminate at the boundary between stable and unstable states but continue across, cutting further integer values of J [*see illustration at top right on page* 85]. An intersection in the stable region indicates the existence of a bound state, meaning a particle that is either stable or metastable. Intersections in the unstable region indicate the existence of resonances, or unstable particles. It can be shown that for strongly interacting particles a particular trajectory joins up real states for either odd or even values of J but not for both. This means that an interval of two units of J must intervene between states on the same trajectory. The lowest state is called an occurrence; higher states can be referred to as Regge recurrences, or as a series of excited rotational states.

How can the existence of a trajectory be demonstrated? In analogy with the spaceship or hydrogen-atom example, one plots the angular momentum J against mass (in Mev) for all the particles that share all the same quantum numbers except J. One can then quickly see whether or not they fall into groups that lie on rising curves. If they do, one has an indication of Regge trajectories. Such trajectories for baryons are illustrated on page 86.

The rule says that only states separated by two full integers can lie on the same trajectory. So far three pairs of states appear to meet this requirement: the two N states, N(939, $1/2^+$) and N(1,688, 5/2); the two Λ states, Λ(1,115, $1/2^+$) and Λ(1,815, 5/2), and the two Δ states, Δ(1,238, $3/2^+$) and Δ(1,920, 7/2). (The spins of the higher Λ and Δ states are not certain; they may be greater than 5/2 and 7/2 respectively.)

In the illustration on page 86 these three pairs of states are connected by slanting colored lines. The black lines represent assumed trajectories on which only one occurrence has so far been definitely discovered. These conjectured trajectories are useful in telling experimenters where to search for baryons of higher angular momentum.

The adjacent illustration on page 87 shows Regge trajectories plotted for mesons. For mesons quantum mechanics tells us to take mass squared rather than mass for the horizontal scale. It will be seen that no Regge recurrences have been discovered as yet, perhaps because meson states of high mass have not yet been studied carefully.

The best evidence for the existence of a Regge trajectory among mesons is based on certain arguments showing that a particular Regge trajectory for a meson state with a Y of 0 and an I of 0 should have an unphysical, or unreal, intersection with a J of 1 and a rest mass of 0. The next lower intersection, at a J of 0, could be physical except that the state would have negative mass squared, which has no meaning. Thus the lowest real intersection should occur at two units of J above 0, that is, at a J of 2. In fact, a meson with a J of 2, designated η(1,250, 2^+), has apparently been discovered within the past year and a half. Its quantum numbers are still uncertain, however. If a Regge trajectory is drawn between η(1,250, 2^+) and its unphysical intersection at a J of 1 and a rest mass of 0, one obtains a crude indication of the slope for the other meson trajectories, shown by the black lines in the illustration. Vigorous experimental efforts are under way to find second members of these meson families, with a J of 2 or 3.

The Eightfold Way

Now we shall turn to another classification scheme that has proved valuable in predicting the existence of previously undiscovered particles. We have seen how the notion of Regge trajectories makes it possible to perceive family connections between particles with different values of J but the same values of all other quantum numbers. Now we shall describe a relation that seems to exist among particles with the same values of J and of parity P but different values of mass, hypercharge Y and isotopic spin I.

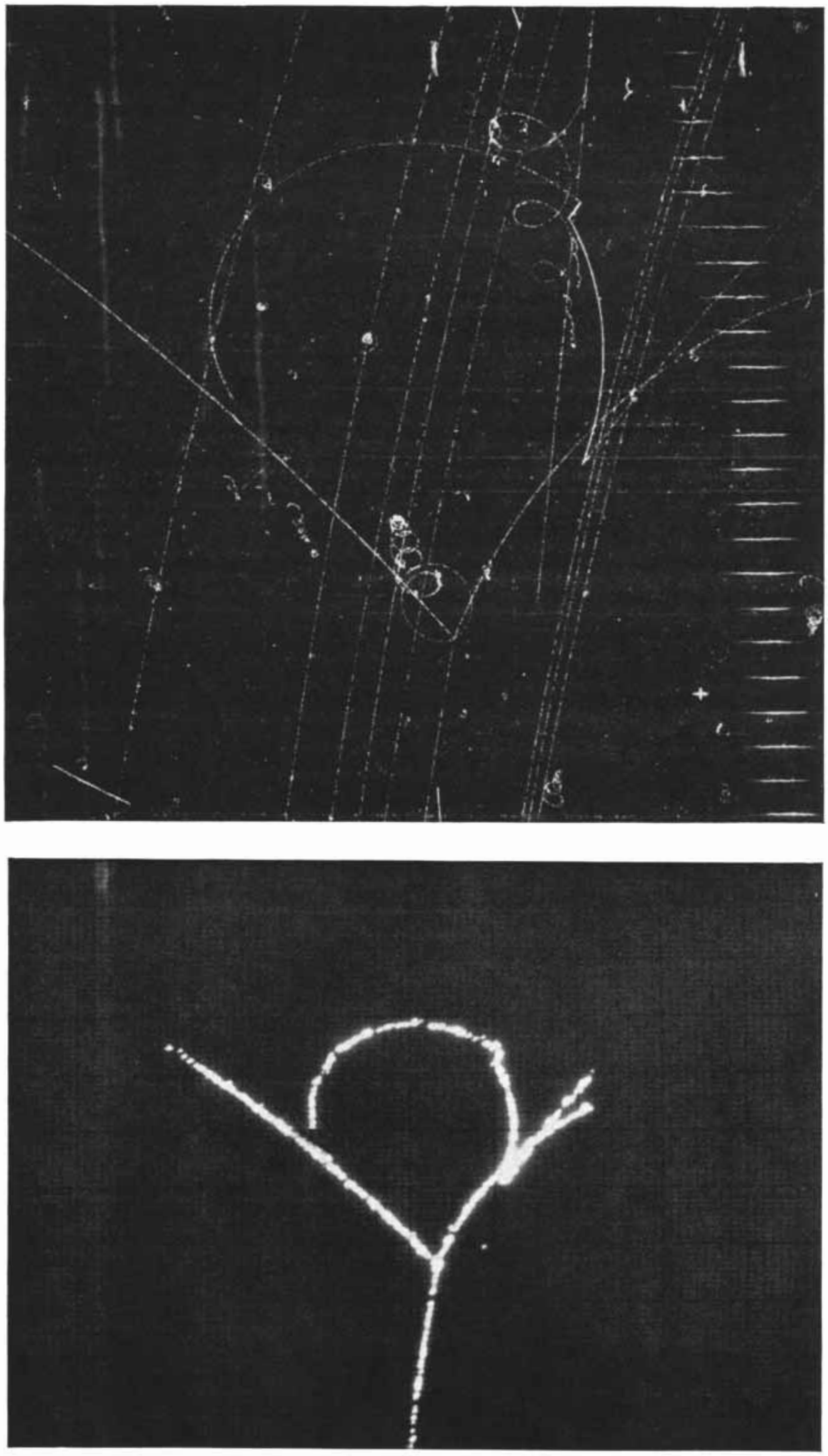
We mentioned earlier that the difference in mass between charge multiplets such as the nucleon doublet (neutron and proton) can be regarded as a "splitting" caused by the fact that isotopic spin is not conserved by the electromagnetic interaction, which underlies the electric charge. This violation produces a maximum mass difference of about 12 Mev in the case of the Σ triplet.

Now, it is a remarkable fact that the four best-known members of the baryon family, N, Λ, Σ and Ξ, are separated by average mass differences only about a factor of 10 greater than that separating members within each multiplet. The gaps in average mass separating the four baryon states are only 77, 75 and 130 Mev respectively. Moreover, these four baryons all seem to have the same J^P; it is $1/2^+$. (Actually the J of Ξ is not firmly established and its parity is still unmeasured.)

If the difference in mass within a multiplet is caused by a violation of the isotopic spin I, is it conceivable that the somewhat greater difference in mass between neighboring multiplets is caused by the violation of the conservation of some other quantum numbers? The kind of solution needed is one in which Y and I are exactly conserved by the strong interaction but certain other conservation laws are broken by some aspect, or some part, of this same interaction. If such a partial violation of new symmetry principles were permitted, one might be able to group baryon multiplets into "supermultiplets" with various values of Y and I but the same J and P. This new system of symmetries would connect different Y and I values in the same way that isotopic spin connects different values of electric charge. The aspect of the strong interaction that violates the new symmetries—represented by new quantum numbers—would split each supermultiplet into charge multiplets of different mass, much as the electromagnetic interaction causes splitting of mass among the members of a charge multiplet by violating isotopic-spin symmetry. The scale of the mass splitting within the supermultiplet, however, would be much greater than that observed within a multiplet, since it is an appreciable fraction of the strong force that is at work rather than the electromagnetic force, which is much weaker.

Early in 1961 an Israeli army colonel and engineer-turned-physicist, Y. Ne'eman, and one of the authors (Gell-Mann), working independently, suggested a particular unified system of symmetries and a particular pattern of violations that made plausible the existence of supermultiplets. The new system of symmetries has been referred to as the "eightfold way" because it involves the operation of eight quantum numbers and also because it recalls an aphorism attributed to Buddha: "Now this, O monks, is noble truth that leads to the cessation of pain: this is the noble *Eightfold Way:* namely, right views, right intention, right speech, right action, right living, right effort, right mindfulness, right concentration."

The mathematical basis of the eightfold way is to be found in what are called Lie groups and Lie algebras, which are algebraic systems developed in the 19th century by the Norwegian mathematician Sophus Lie. The simplest Lie algebra involves the relation of three



BUBBLE-CHAMBER EVENT (*top*) is typical of more than 300,000 measured annually at the Lawrence Radiation Laboratory of the University of California at Berkeley. Many events are measured with the help of a Scanning and Measuring Projector. This device, which is linked to a computer, gives step-by-step instructions to the measurer and redisplays what he has measured on a cathode-ray screen (*bottom*). The photograph shows a K^- meson entering from the bottom and striking a proton in the 72-inch bubble chamber. The reaction creates a K^0, a proton and a π^-. The proton curves to the left, the π^- to the right in the chamber's magnetic field. The K^0 leaves no track, but after going about 10 centimeters it decays into a π^+ and π^-. The π^+ curves counterclockwise and comes to rest. After 10^{-8} second it decays into a μ^+, which goes only about one centimeter and comes to rest. After 10^{-6} second the μ^+ decays into an e^+, a neutrino and an antineutrino. The large curve at the top of the photograph and the oscilloscope redisplay is the path of the e^+.

components, each of which is a symmetry operation of the kind used in quantum mechanics. Isotopic spin consists of three such components (I_+, I_- and I_z) related by the rules of this simplest algebra. The algebra is that of the Lie group called SU(2), which stands for special unitary group for arrays of size 2 × 2; there is one condition in the 2 × 2 arrays that reduces the number of independent components from four to three (hence the term "special").

The component operations of the eightfold way satisfy the mathematical relations of the next higher Lie algebra, which has eight independent components. Here the Lie group is called SU(3), which stands for special unitary group for arrays of size 3 × 3; again a special condition reduces the number of components from nine to eight. The eight conserved quantities of the eightfold way consist of the three components of isotopic spin, the hypercharge Y and four new symmetries not yet formally named. Two of the new symmetries change Y up or down by one unit without changing electric charge; the other two symmetries change both Y and electric charge by one unit [*see illustration on page 88*]. The violation of all four new symmetries by part of the strong interaction changes the masses of the multiplets forming a supermultiplet. An example of a supermultiplet (an octet) is provided by N, Λ, Σ and Ξ, if indeed they all have an angular momentum J of 1/2 and positive parity, that is, a J^P of $1/2^+$.

The kind of violation suggested by the eightfold way leads to a rule connecting the masses of a supermultiplet, provided that the violation is not too severe. The rule for N, Λ, Σ and Ξ is that 1/2 mass N plus 1/2 mass Ξ equals 3/4 mass Λ plus 1/4 mass Σ. Substituting the actual masses of the four particle states gives 1,129 Mev for the left side of the equation and 1,135 Mev for the right side. The agreement with the approximate mass rule is surprisingly good.

This apparent success suggested a search for other octets. At the beginning of 1961 the only meson multiplets certainly known were π, κ and $\bar{\kappa}$, all with a J^P of 0^-. They just fit the octet pattern if one adds a neutral singlet meson with a predicted mass of 563 Mev. (The masses are predicted as they are for baryons except that for mesons the masses in the equation must be squared.) Late in 1961 the η meson was found, with a mass of 548 Mev. Later its J^P was determined to be 0^-, as required.

Meanwhile, mesons with a J^P of 1^- were turning up: the $\pi(750, 1^-)$ triplet and the $\kappa(888, 1^-)$ and $\bar{\kappa}(888, 1^-)$ doublets. Once more the octet pattern was appearing, and the existence of a neutral singlet with a mass of about 925 Mev was expected. Very soon experiments revealed the $\eta(1^-)$ meson, but its mass was only 782 Mev. The mass rule, so successful before, had mysteriously failed.

The mystery may since have been cleared up somewhat. The octet is only one of several supermultiplets allowed by the eightfold way. Another possibility is a lone neutral singlet with a Y of 0 and an I of 0. Suppose there were such a meson with a J^P of 1^-, which we call $\eta'(1^-)$. If its mass value were near that of $\eta(1^-)$, only the broken symmetries of the eightfold way would distinguish the two particles. Under these conditions quantum mechanics predicts that a kind of "identity crisis" would set in, making each of the mesons assume to some extent the properties of the other one. Moreover, the masses would be affected by this sharing of properties, and one meson would have a higher mass, the other a lower mass, compared with the simple case in which the rule for the octet holds. The predicted mass squared for $\eta(1^-)$, or $(925)^2$, should then lie roughly halfway between the actual values of mass squared for $\eta(1^-)$ and $\eta'(1^-)$. Since the actual mass of $\eta(1^-)$ is 782 Mev, one might expect to find another meson, $\eta'(1^-)$, with a mass of around 1,045 Mev. Indeed, in 1962 such a meson with the right values of Y and I (both 0), and with a mass of 1,020 Mev, was discovered independently by two groups of physicists. There is actually no clear way to decide which of the two η mesons, $\eta(782)$ or $\eta(1{,}020)$, belongs to an octet and which is the singlet. We assume that nature is as perplexed as we are.

The $\eta(1{,}250, 2^+)$ meson, the most recently found of the mesons shown in the chart on pages 76 and 77, seems to be a singlet. Thus the 18 mesons listed can be accounted for as two octets and two singlets. Not all the experimental facts are certain, however, and the picture, particularly the identity crisis of $\eta(1^-)$ and $\eta'(1^-)$, must still be considered tentative.

Returning to the baryons, what other supermultiplets have been found beyond the original one containing N, Λ, Σ and Ξ? Λ(1,405) seems to be a singlet; its J^P has not been definitely established. N(1,688, 5/2), the first Regge recurrence of the nucleon, should, like the nucleon, belong to an octet containing other Regge recurrences of Λ, Σ and Ξ. The Λ member of this excited octet may well be Λ(1,815), if indeed it has a J^P of $5/2^+$. The Σ and Ξ members are now being sought; if one of the two particles can be found, the mass of the other can be predicted approximately by the octet mass rule.

N(1,512, 3/2) may also belong to an octet. Another probable member has already been found: $\Lambda(1{,}520, 3/2^-)$. It is possible that Σ(1,660) has a J^P of $3/2^-$. If this assignment is correct, the octet mass rule predicts a Ξ multiplet with a mass around 1,600 Mev. Here, however, the experimental situation is very uncertain.

That brings us to Δ(1,238), the unstable baryon discovered in 1952. Since it is a quartet, it cannot belong to either the octet or the singlet pattern. The simplest supermultiplet permitted by the eightfold way into which it can fit is a 10-member group, or decuplet, consisting of a Δ quartet, a Σ triplet, a Ξ doublet and an Ω singlet [*see "c" in illustration on page 88*]. For decuplets the mass rule predicts approximately equal mass spacing between members of the supermultiplet. Since Σ(1,385) is thought to have a J^P of $3/2^+$, it could very well belong to a decuplet with Δ(1,238). The equal-spacing rule predicts a Ξ particle at about 1,532 Mev. The discovery of Ξ(1,530), with a J^P probably of $3/2^+$, appears to be a striking confirmation of the prediction. The mass rule further predicts an Ω particle at about 1,676 Mev, which would be the only particle state consisting of a negative charge singlet. Such a particle would actually be stable under strong and electromagnetic interactions, since it would lack the energy to decay into any of the channels with which it communicates. Thus it should live about 10^{-10} second and decay by weak interactions. It is now being sought eagerly. If it is found, the correctness of the eightfold way will be strikingly established.

We close this section with the remark that the symmetry game may not yet be finished for strongly interacting particles. For example, there might exist some undiscovered quantum number that is conserved by the strong interactions and that has the value 0 for all known particles. Before strange particles were discovered, the strangeness quantum number (equivalent to Y) was of this kind. Experiments at very high energies with the next generation of accelerators might produce a similar situation with respect to an entirely new quantum number.

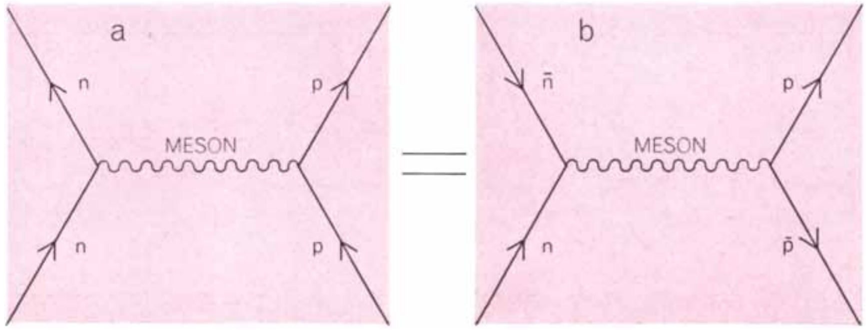
Composite Particles

The meaning of the term "elementary particle" has varied enormously as man's view of the physical universe has become more detailed. In the past few years it has become increasingly awkward to consider several scores of particles as elementary. Evidently a reappraisal of the entire elementary-particle concept is in order.

Let us begin by asking why we feel sure that certain particles such as the hydrogen atom are *not* elementary. The answer is that even though these particles have properties qualitatively similar to those of neutrons, protons and electrons, it has been possible theoretically to explain their properties by assuming that they are composites of other particles.

The hydrogen atom itself provides an outstanding example of what is meant by composite, because its properties have been theoretically predicted with enormous accuracy. It is important to realize that the hydrogen atom is not exactly composed of one proton and one electron. It is more accurate to say that it is so composed *most* of the time. The ground state of the hydrogen atom is a stable "particle" that communicates (via strong, electromagnetic and weak interactions) with a great variety of closed channels, of which electron plus proton is the most important. According to quantum mechanics any state consists part of the time of each of the channels that communicate with it. As an example, for a certain small fraction of the time the ground state of the hydrogen atom consists of the expected electron and proton plus an electron-positron pair. The effect of this channel on the energy of the atom is tiny, but it has been calculated and measured; the agreement is excellent. There are infinitely many other closed channels that contribute to the structure of the hydrogen atom, but fortunately their effect is negligibly small.

In strongly interacting systems complicated channels are more important. For example, the properties of the deuteron (A equals 2) have been predicted, assuming that this particle is a composite of neutron and proton, but here the accuracy of the predictions is much poorer than it is for the hydrogen atom because the effect of additional channels (involving pions, say) is substantial. Nevertheless, there is a general belief that, since the simplest channel accounts for the bulk of the observed properties of the deuteron, it should eventually be possible to improve the predictions systematically by inclusion of more channels. The same kind of statement can be made for all nuclei heavier than the deuteron, and there is no disposition to re-



"CROSSED REACTIONS" illustrate the close correspondence between the concept of a force and the concept of a particle. Reaction *a*, which is read upward, represents a scattering collision between a neutron and a proton. The meson "exchanged" represents the strong force acting between two baryons. Reaction *b*, which is read from left to right, is a crossed reaction of *a*. It shows a meson acting as an intermediate particle in a reaction that converts a neutron and antineutron into a proton and antiproton. The two reactions are equivalent.

gard any of these compound nuclei as "elementary."

Confusion about the distinction between composite and elementary particles has arisen for particles with an A of 0 and 1 (mesons and baryons) because here one rarely has a single dominant channel nearby in energy. Consider one of the worst cases: the pion. The communicating channel with the lowest threshold is a 3π configuration; some channels with still higher thresholds are 5π, κ plus $\bar{\kappa}$ plus π, N plus $\overline{\text{N}}$, and Ξ plus $\overline{\Xi}$. Hence part of the time the pion exists as 3π, part of the time as κ plus $\bar{\kappa}$ plus π, and so forth.

All the relevant thresholds are much higher than the pion mass, and many rather complicated closed channels contribute substantially to the pion state. The result is that even a rough calculation of pion properties has not yet been achieved. A more favorable case is that of $\pi(750)$, where the 2π channel is believed to dominate; but even here a glance at the illustration on page 79 shows that there are many nearby channels to be reckoned with.

We may nevertheless employ the operational definition: a particle is nonelementary if all its properties can be calculated *in principle* by treating it as a composite. Such a calculation must yield various probabilities for the various closed channels; the binding forces in these channels must yield the right mass for the particle.

The problem of including all the significant channels is in most cases still too difficult, but suppose the calculation could be carried out. Would we then get a correct description of each particle? Would the quantum numbers and the mass come out right? Until recently there was an almost universal belief that a few strongly interacting particles, including the nucleon, could not be calculated on such a basis. In the present theory of electrons and photons, which gives such an excellent description of electromagnetic phenomena, the properties of the electron and photon cannot be dynamically predicted. The reason is that the known forces are not powerful enough to form bound states with masses as small as those of the electron and the photon.

Reasoning by analogy, theorists tended to give the nucleon a special status parallel to that of the electron. Thus they were inhibited from trying to treat the nucleon as a composite particle. Gradually, however, this select status seemed increasingly dubious. And when an attempt was finally made to calculate the properties of the nucleon from an analysis of its communicating channels, the same qualitative success was achieved as with the deuteron and the $\Delta(1{,}238)$ particle, which had for years been called composite just because it had first been observed in a pion-proton scattering experiment.

It seems, furthermore, on the basis of recent developments in which the concept of the Regge trajectory plays an important role, that in all such dynamical calculations no distinction need be made on the basis of the angular momentum or other quantum numbers of the particle involved. If there is no need for an aristocracy among strongly interacting particles, may there not be democracy?

"Bootstrap" Dynamics

Composite particles owe their existence to the forces acting in channels with which the particles communicate. How do these forces arise and how can they be calculated?

The key concept behind the calculation is "crossing." Consider the following reaction involving four particles:

$$a + b \longleftrightarrow c + d$$

This says that the channel *a,b* is coupled to the channel *c,d*. The probability that this reaction will take place (in either direction) is expressed mathematically as the absolute value squared of the "reaction amplitude," which depends on the energies of the four particles involved. The principle of crossing states that the same reaction amplitude also applies to the two "crossed" reactions in which *ingoing* particles are replaced by *outgoing* antiparticles (indicated by a bar over a letter) thus:

$$a + \bar{c} \longleftrightarrow \bar{b} + d$$
$$a + \bar{d} \longleftrightarrow \bar{b} + c$$

These different reactions are distinguished by the signs of the energy variables, which are positive or negative according to whether ingoing or outgoing particles are involved, but if the reaction amplitude is known for any one of the three reactions, it can be obtained for the other two by inserting the proper signs for energy.

An example of crossing is the following pair of reactions involving neutrons and protons:

$$\text{(a)}\quad n + p \longleftrightarrow n + p$$
$$\text{(b)}\quad n + \bar{n} \longleftrightarrow p + \bar{p}$$

Both reactions are described by the same reaction amplitude, an important aspect of which can be depicted diagrammatically, as shown in the illustration on this page. The first way of drawing the arrows in this diagram is appropriate to reaction *a* and the second to reaction *b*. The two figures differ, of course, only in the direction one reads them, either from bottom to top or left to right, as indicated by the arrowheads.

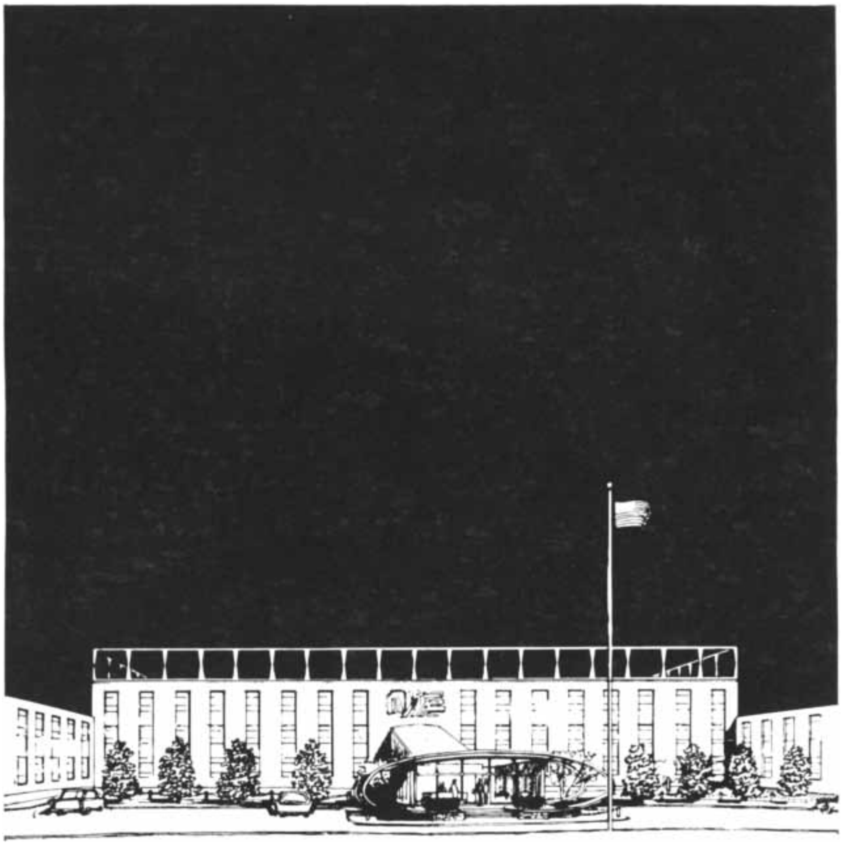
One interprets the first figure by saying that in a scattering collision between a neutron and a proton a meson is "exchanged," and it can be shown that this exchange is a way of representing the force acting between those two baryons. The interpretation of reaction *b* is that a meson that communicates with both the $n,\bar{n}$ and $p,\bar{p}$ channels provides a means for connecting the two channels of the reaction. Thus a single diagram corresponds both to a force in one reaction and to an intermediate particle in the crossed reaction. It follows that forces in a given channel may be said to arise, in general, from the exchange of intermediate particles that communicate with crossed channels.

With this as background we return to the idea mentioned in the introduction to this article, that the strongly interacting particles are all dynamical structures that owe their existence to the same forces through which they mutually interact. In short, the strongly interacting particles are the creatures of the strong interaction. We refer to this as the "bootstrap" hypothesis. It was formulated by one of the authors (Chew) and S. C. Frautschi at the University of California at Berkeley.

According to the bootstrap hypothesis each strongly interacting particle is assumed to be a bound state of those channels with which it communicates, owing its existence entirely to forces associated with the exchange of strongly interacting particles that communicate with crossed channels. Each of these latter particles in turn owes its existence to a set of forces to which the first particle makes a contribution. In other words, each particle helps to generate other particles, which in turn generate it. In this circular and violently nonlinear situation it is possible to imagine that no free, or arbitrary, variables appear (except for something to establish the energy scale) and that the only self-consistent set of particles is the one found in nature.

We remind the reader that in electromagnetic theory a few special particles (leptons and photon) are *not* treated as bound (or composite) states, the masses and coupling characteristics of each particle being freely adjustable. Conventional electrodynamics, as far as anyone knows, is not a bootstrap regime.

It is too soon to be sure that free variables are absent for strong interactions, but we shall close in an optimistic spirit by mentioning a fascinating possibility that would represent the ultimate contribution of the bootstrap hypothesis. If the system of strongly interacting particles is in fact self-determining through a dynamical mechanism, perhaps the special strong-interaction symmetries are not arbitrarily imposed from the outside, so to speak, but will emerge as necessary components of self-consistency. It is remarkable, and puzzling, that isotopic-spin symmetry, strangeness and now the broader eightfold-way symmetry have never been related to other physical symmetries. Perhaps their origin is destined to be understood at the same moment we understand the pattern of masses and spins for strongly interacting particles. Both this pattern and the puzzling symmetries may emerge together from the bootstrap dynamics.



THE ANTARCTIC SKUA

This large bird is found closer to the South Pole than any other living thing except man. It has made itself unpopular by defecating on explorers and preying on the lovable penguin

by Carl R. Eklund

The Antarctic skua has the distinction of having been seen closer to the South Pole than any other bird. In keeping with its extraordinary choice of dwelling place, the south polar skua is also unusual in physique and habits. It is a giant among birds, with a wingspread of some four and a half feet. Known as "the eagle of the Antarctic," it is one of the boldest and most ferocious defenders of home and family in the avian world. It is monogamous, mating year after year with the same partner. And for its nesting place, where it hatches and raises its young, it chooses the world's coldest climate.

The name "skua" comes from *skúfa,* an Old Norse word meaning "to push aside." One of the earliest descriptions of the Antarctic skua was given by Herbert G. Ponting, the photographer with Robert Falcon Scott's ill-fated South Pole expedition of 1911 and 1912, whose members saw skuas only 160 miles from the Pole. Ponting wrote of the skuas in his book *The Great White South:*

"They were extremely noisy and of a most quarrelsome disposition.... By outward and visible signs, the skua-gull is a gentleman, and his mate a dainty, well-dressed lady—appearances being thus deceptive, for, except for their looks and cleanliness, there is nothing refined about either male or female; both are scamps and malefactors [in] the disgusting practice they had...of vomiting [Author's Note: Actually defecating] on interlopers. They would fly towards us from the rear, and, carefully making allowance for speed and distance, discharge a nauseating shower of filth...I was more than once the victim of this revolting habit—whilst the air was rent by what sounded to me very much like screams of sardonic laughter."

The skuas did not hesitate to attack the human intruders by dive-bombing. Ponting reported:

"I received two blows in rapid succession, one on the back of the head and the other in the right eye.... Two more blows were delivered, one just at the back of the ear, which almost bowled me over."

Members of a French expedition in Antarctica from 1948 to 1953 had an even stronger reaction against the skua. The leader of the expedition, Mario Marret, wrote in his *Seven Men among the Penguins:*

"At our housewarming [the doctor] raised his glass and proposed that the first political act of the new government of Adélie Land should be a declaration of war against skuas.... The proposal was adopted with acclaim and...hostilities were opened by placing a homemade bomb where the skuas were accustomed to assemble. The fuse was lighted from our hut and while we waited for the explosion we drank confusion to all skuas and sang our national anthem."

One of the unattractive features of the skua is that it preys on the eggs and chicks of the Adélie penguin, which has a special charm for the human species. This, of course, has contributed to the skua's bad reputation among Antarctic explorers.

The skua is not really a gull; it belongs to the family of jaegers. Most ornithologists divide the skuas into two species: the south polar skua, called *Catharacta maccormicki,* and the great skua, which has three subspecies—the well-known Arctic skua of the Northern Hemisphere, the Chilean skua of Temperate Zone South America and the brown skua of the sub-Antarctic region.

The south polar, or McCormick, skua was not much studied until recently, but as a result of activities in the Antarctic during the International Geophysical Year it became the object of one of the most widely international bird studies ever conducted. Investigators from the U.S., the U.S.S.R., the United Kingdom, Australia, New Zealand, Argentina, Chile, France, Japan, Norway, South Africa and Belgium joined in a co-operative program of banding and observing this "buccaneer of the South." The banding started in the Antarctic summer of 1955 and 1956 and has been continued since the IGY by the U.S. Antarctic Research Program Bird Banding Program, in close co-operation with the U.S. Fish and Wildlife Service. The National Science Foundation has provided financial support. More than 6,000 skuas have been banded so far.

The bird, in spite of its aggressiveness (or rather because of it), is easy to catch. It can be plucked out of the air with a hand net as it dives to defend its nest; it can be snared on the ground with a loop suspended from a pole; it has been captured en masse by throwing a large net over a group of feeding birds by means of three guns fired simultaneously.

Each bird is banded with a numbered metal strip and with a plastic strip of a distinctive color that identifies the station, and consequently the locality, where it was banded. In addition, some birds have been marked with paint to make it easier to follow their movements. The first such bird recovered was one that had been dyed red at the U.S. Wilkes Station; it was appropriately recovered by Soviet workers.

My own introduction to the south polar skua came during Richard E. Byrd's expedition of 1939, 1940 and 1941 to the Palmer Peninsula area of Antarctica, when I was ornithologist with the expedition. Later, as scientific leader of Wilkes Station in 1956, 1957 and 1958, I took part in the co-operative international study of the bird and was able to work out some of its life history.

In color the south polar skua is rather undistinguished: its dark brown to light brown plumage is highlighted only by a large white patch on its primary wing feathers. Because the newly hatched chick is slate gray, it blends into the gray rocks in which its nest is built. This protective coloring serves to help preserve the chick, not against other predators—the skua has none—but against members of its own species!

The south polar skua is its own predator, cannibalizing chicks in the nests of its skua neighbors, which perhaps is not surprising in a desolate part of the world where the food supply is limited. Weather disturbances, however, kill even more of the chicks. Altogether the mortality of skua chicks is high, particularly where two chicks are hatched in the same nest. In the 40 nests we observed closely, of the 42 chicks successfully hatched from the eggs only 34 survived beyond four weeks—a 23 per cent mortality in the nest. The skua's nest is merely a small depression scooped out in the pebbles on the ground. To test the effect of the chicks' coloring I dyed some of them a vivid color: pink, purple or yellow. Only half of these chicks survived, whereas most of their natural-colored, inconspicuous contemporaries in other nests in the same area escaped the cannibal attentions of adult skuas.

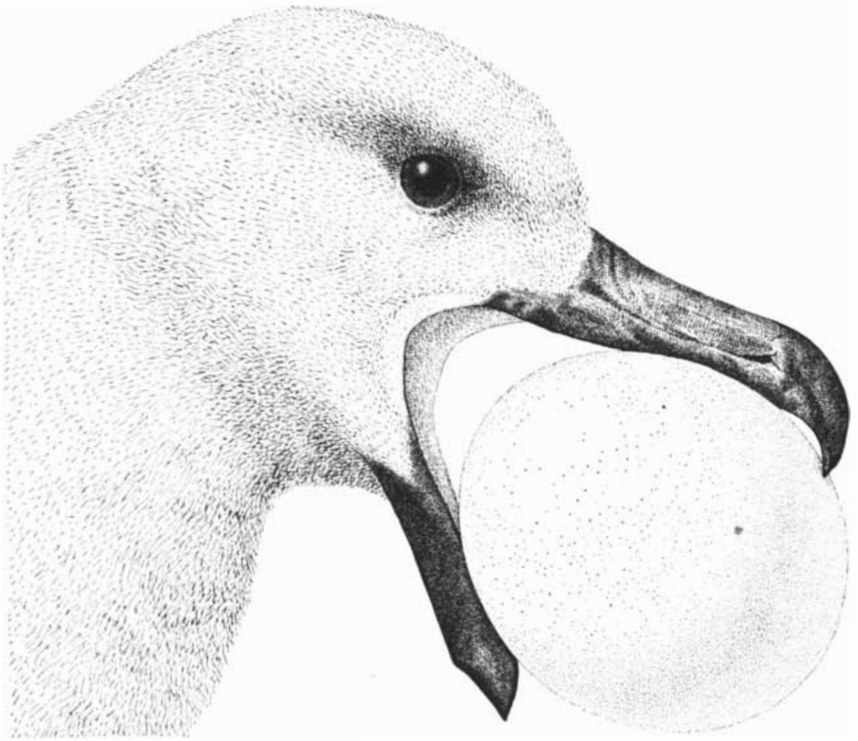
Fierce as the skua is in defending the chicks in its own nest, its loyalty does not extend to the rest of its species. One might say that this very tendency to prey on its own species is responsible for the skua's ferocious defense of the nest. Breeding in a region where it does not need to fear any other predator, the bird must nevertheless be constantly on guard against assassins of its own species.

The annual cycle of the south polar skua follows its food supply. In the nonbreeding season—the Antarctic winter—the bird lives on the pack ice off the Antarctic continent and feeds on marine life, particularly red krill: the tiny floating animals that are also the basic food of whales. In October, shortly after the Adélie penguins begin their spring migration into the continent, the skuas follow them [see "Penguins," by William J. L. Sladen; SCIENTIFIC AMERICAN, December, 1957]. The skuas arrive just when the Weddell seals are pupping, and they eat the seals' placentae. Then, in early November, when the penguins begin to lay their eggs, these eggs, and later the penguin chicks, become primary items in the skuas' diet. In the Antarctic fall the penguins leave, and a few weeks afterward, around the middle of April, the skuas also go back to their winter homes off the continent.

The summer breeding grounds of the skuas, and also of the Adélie penguins, are within 25 degrees of the Pole, in a region where during the warmest month the mean temperature is only 32 degrees Fahrenheit. The skuas generally nest close to the penguins; more than 95 per cent of their nests have been found around the edges of penguin rookeries. Each pair of skuas establishes a territory at least 50 feet in diameter, from which it excludes all intruders, and proceeds to scoop out several shallow depressions in the bare ground. One of these is finally chosen as the nest, apparently by the female. She then begins to lay eggs, usually during the third week in November. She lays one or two at a time: in 80 per cent of the cases she has a clutch of two eggs. The male and female share the job of sitting on the eggs (unlike the Emperor penguin, whose lordly male sits on a single egg for 63 dark, cold, lonely days in winter). The female skua takes

SOUTH POLAR SKUA spreads wings and opens beak in aggressive display. It ranges in color from dark brown to very light brown. The bird has a wingspread of 4½ feet and weighs about three pounds. Photograph was made at Wilkes Station on the Antarctic coast.

SKUA IN FLIGHT displays its large wingspread. Photograph was made by William J. L. Sladen of Johns Hopkins University, joint director with the author of bird-banding program.



SKUA CARRIES EGG of penguin in its beak without breaking it in this life-size drawing based on a photograph made in 1911 by Herbert G. Ponting of Robert Falcon Scott's party.

over the major part of the chore, averaging more than three times longer on the eggs than the male, while the male spends most of his time defending the nest. About 30 days are required for the eggs to hatch.

Like all birds, the skua has a high rate of metabolism. Its body temperature is higher, however, than that of any other Antarctic bird: it averages 106.1 degrees F. Its eggs are slightly larger than a good-sized chicken egg. To measure the temperature at which the skua incubates its eggs we used an unusual device: an electronic thermometer that was placed in the egg and "broadcasted" a continuous record of the temperature. This instrument emitted radio pulses whose frequency was modulated by the internal temperature of the egg. To insert it, we punctured the ends of the egg, removed the contents and carefully cut the empty shell in half. After placing the transmitter inside, we taped the halves together and returned the egg to the nest. The pulses from the broadcasting egg were picked up by a loop antenna over the nest and were tuned in and counted at intervals over a nine-day period. The record showed that the temperature of the skua's eggs averaged 96.6 degrees F., with a high of 103.5 degrees and a low of 87 degrees, whereas that of incubating penguin eggs, recorded for comparison, averaged 92.7 degrees.

We tried removing and substituting eggs in the skuas' nests to see how they would react. When an egg was taken out and placed about a foot away, the setting bird would usually pick it up and put it back in the nest. When a third egg was added to its own pair, the bird would try to hatch it with the others. When a penguin egg (which is white and larger than a skua egg) was substituted for one of the skua's own, the bird sat on it without apparently noticing any difference.

To see if the skua parents would treat chicks with the same impartiality after they were hatched, we conducted a game of musical chairs. I had injected a red vegetable dye in one egg of a pair in a nest so that the chick would be red when it hatched. After both eggs had hatched I put the gray chick in a nearby nest with the single chick that occupied it. The parents of the latter dutifully cared for both. The next day I removed these two and substituted the red chick in their place. As if nothing had happened, the foster parents fed and raised the red chick until it could fly.

Skua parents feed their young by regurgitating the food they have collected and depositing it on the ground, where the chicks pick it up. Examination of this food shows that it consists of fish, red krill, penguin meat and an occasional skua chick. According to observations of marked birds, the skuas often cover a wide range—eight miles and probably much more—in search of food for the chicks. The parents will combine to steal eggs from penguin nests: while one skua draws a penguin away from its nest, the other darts in and carries an egg away in its beak. It punches a hole in the egg and both robbers then take turns feeding through it. It may seem strange that the Adélie penguin is able to survive the constant preying of the skuas, but actually the penguins far outnumber their predators. There is evidence that the skuas in fact strengthen the penguin stock by preying mainly on the weaklings among the penguin young.

Skuas are able to detect meat at a considerable distance. Edward A. Wilson, the ornithologist with the Scott expedition in 1911 and 1912, reported that after the explorers had had to kill a sledge dog they had found a skua feeding on the animal the next day, although the nearest open water, where skuas are normally found, was 170 miles away. I had a somewhat similar experience during a dog-sledging trip in 1940; on that occasion the dead dog promptly attracted a skua although we were 100 miles from open water. Wilson believed that skuas must be attracted to meat at such great distances through an extraordinary sense of smell. I disagree. My own studies indicate that the bird finds it by virtue of uncannily sharp eyesight. In one experiment we put some fresh meat in a clear plastic bag on the ground. Although no odor could pass through the plastic, skuas flying overhead promptly spotted it, tore open the bag and got the meat. On the other hand, when we simply hid fresh meat from sight by covering it with loose, powdery snow, skuas passed it by, evidently not having detected it although it could be smelled through the snow.

The skua's defense of its nest is its most conspicuous behavioral feature. I myself had many occasions to observe this. It makes no difference to the skua parents whether the chick in their nest is their own or a substituted foster child; they fight for it fiercely in either case. What they defend is the territory they have claimed. A pair of skuas will continually harass any intruder in this territory. Diving from a height of 100 to

SKUA SWOOPS DOWN to capture Adélie penguin chick in photograph by Richard L. Penney of Johns Hopkins University. A healthy chick can fend off an attack by a single skua.

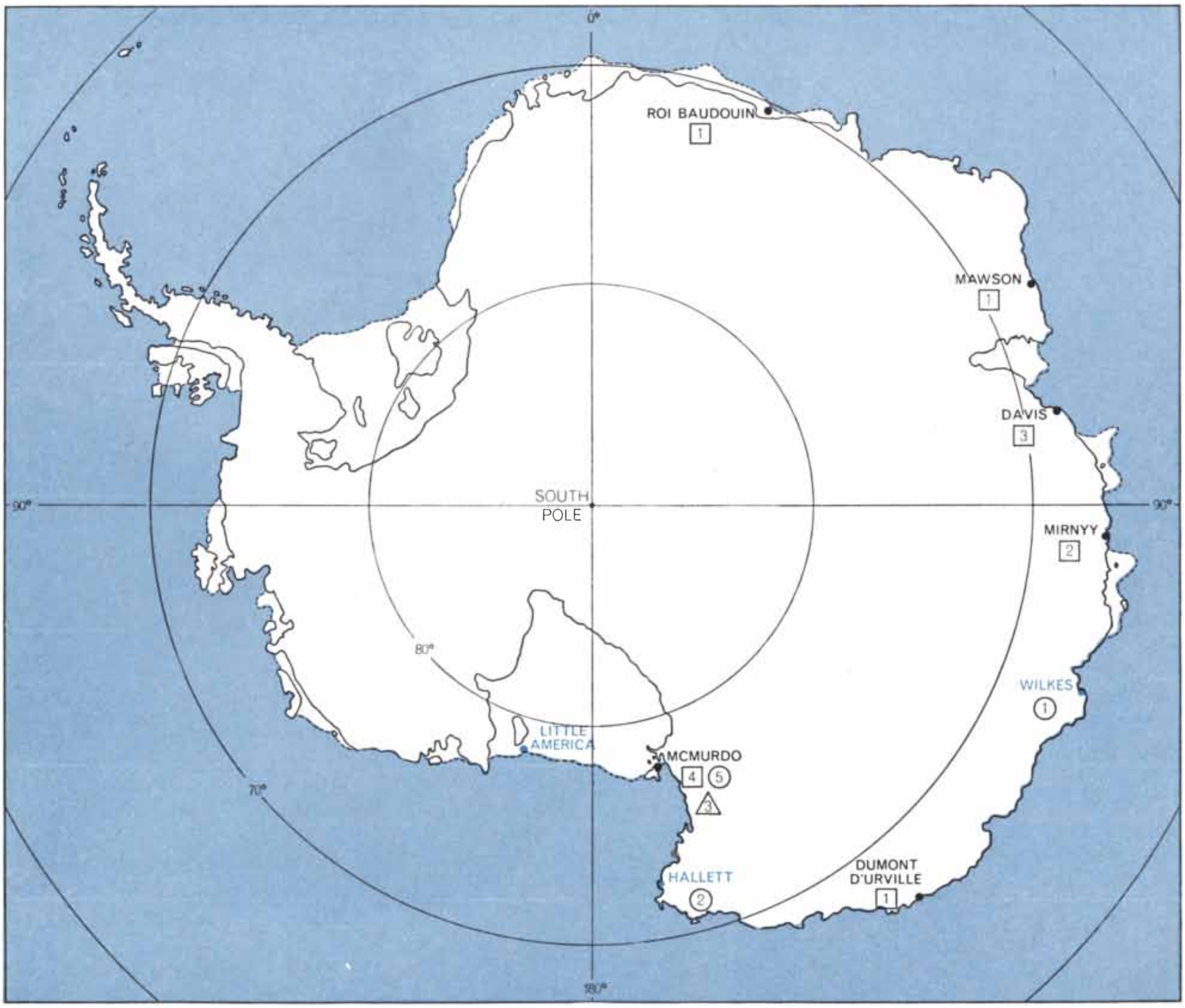
SKUA CHICK AND EGG were also photographed by Penney. The nest of the skua is simply a depression among small stones. The chick is slate gray and hard to see from a distance.

150 feet, the bird usually makes only a threatening pass close to its target, but often it will hit a man on the head with its feet or a wing. I was hit so many times that I finally resorted to wearing a long feather in my cap; thereafter the skuas contented themselves with hitting the feather instead of my head. My companions nicknamed me "the bald eagle." The skuas' dive-bombing tactics made catching them with a hand net a favorite sport in Antarctica. I caught several hundreds of the birds in this fashion.

The banding of the skuas brought to light a remarkable fact. Young skuas, in the first years after they are born, may wander about to different summering sites from season to season. But when they begin to breed, apparently at about the age of five, they tend to come back to the area where they were born. In any event, once mature skuas have built their nests in a certain location they establish an amazingly tenacious attachment to it and come back to nest in the same area year after year. Of 277 skuas banded near Wilkes Station in the summer of 1956 and 1957, more than half returned to the same place the following spring. What is more, the skua tends to come back and mate with the same partner, although they have separated during the winter. Apparently the south polar skuas mate for life and take a new partner only when the old one has died. Of 19 pairs banded and marked as couples in the 1956–1957 season, 14 came back to Wilkes Station and remated the following year. Four of the other five pairs did not show up at all; of the fifth pair, one bird came back with a new partner, its old one presumably having failed to survive the winter. Of the 14 pairs that remated, six came back and remated together the third season and five the fourth season—a remarkable record of marital faithfulness in the animal world.

The south polar skua's habit of coming back to breed in the same grounds year after year must keep the species extraordinarily inbred. Wherever it may travel and however much it may mix with its fellow skuas during the other seasons, its isolation in a particular site for the breeding season prevents any wide mixing of genes or spread of genetic changes.

In 1957 I undertook to test the homing instinct of the skua by taking one member of a nesting pair to a 4,200-foot



RECOVERIES OF BANDED SKUAS away from areas of banding since 1957 are few, indicating that the birds return to same nesting areas each year. Birds banded at Wilkes and recovered elsewhere are indicated by a square; banding at Hallett is represented by a triangle and at Little America by a circle. The number within symbol is the number of birds recovered at the station; for example, four skuas banded at Wilkes Station have been found at McMurdo. The names of the three banding stations are in color.

plateau 51 miles away on the ice-covered continent and releasing it there. It was back in its nest within 48 hours. In the Antarctic summer of 1962 Robert Wood, a biologist working at Cape Crozier on Ross Island near McMurdo Sound, carried out an experiment that produced a much more remarkable demonstration of the bird's direction-finding ability. He took six adult skuas from six different nests; they were flown by airplane to the South Pole, 825 miles away, and released at an elevation of 9,200 feet above sea level. The birds were observed to have difficulty in taking off from the ground, possibly because of the elevation. But within 10 days one of these birds made its way back to its nest at Cape Crozier.

What is most remarkable about this feat is that there were no landmarks within hundreds of miles of the release point and at the South Pole every direction is north! It was the first time in history that a test of a bird's navigational ability had been made at either Pole.

We were able to estimate the populations of skuas and of Adélie penguins in habitable areas of Antarctica by various methods. In the Windmill Islands area the count indicated a total population of about 2,300 skuas and about 155,000 nesting penguins—a ratio of one skua to some 68 penguins. At Cape Hallett, where the U.S. and New Zealand established a joint station, the penguin population within a 55-acre tract was estimated at 215,000 and the ratio was roughly one skua to 360 adult penguins.

The recoveries of young banded birds at various stations have shown that some of them wander for hundreds and even thousands of miles along the Antarctic coast. There is no evidence so far, however, that they migrate to any other continent. Five dead south polar skuas have been found in Australia and New Zealand, but these apparently were blown there by storms. It seems that the bird spends its entire lifetime within the Antarctic region—the six warmer months on the continent itself, where it breeds, and the six colder months no farther away than the limits of the pack ice that surrounds the continent. A truly polar bird, the south polar skua.

BANDING A SKUA may involve a struggle. Here Robert Wood of Johns Hopkins University is finishing the job. Picture was made by Sladen at Cape Crozier, near McMurdo Sound.

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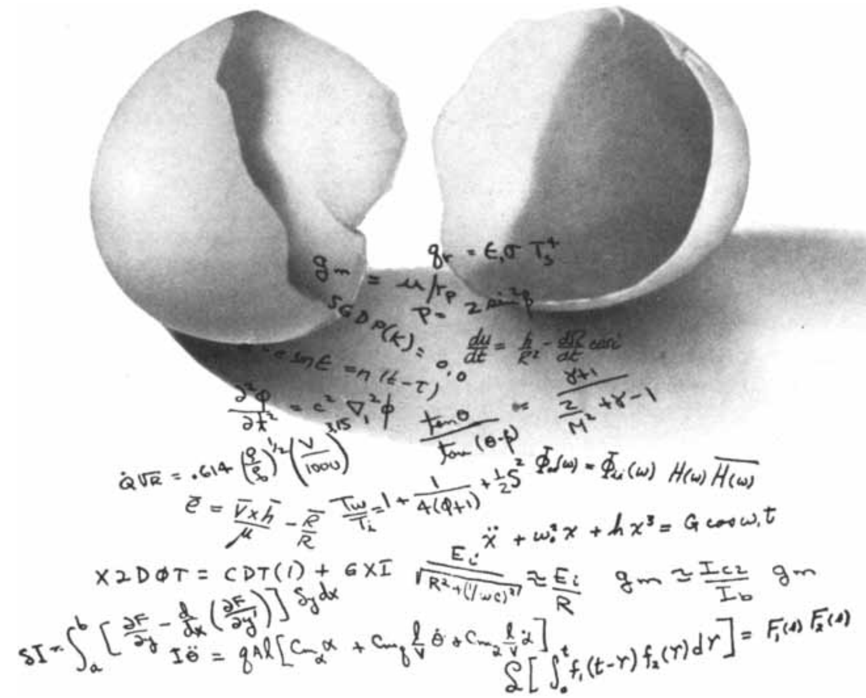


Redundancy in Computers

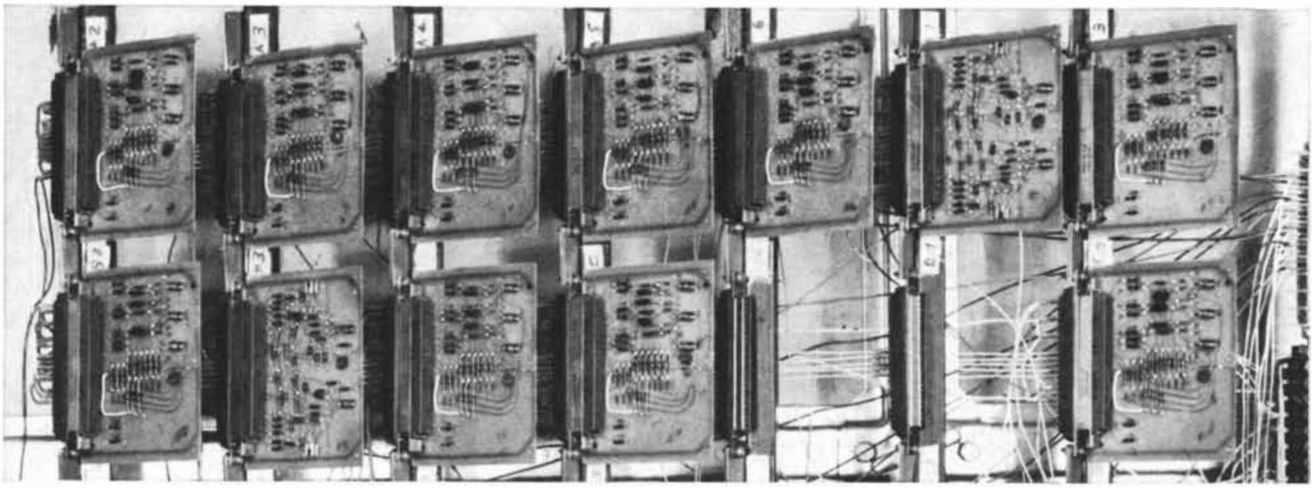
One way to make a machine or a biological system more reliable is to design it to work even if some parts fail. This requires extra parts, so arranged that they interact to suppress errors

by William H. Pierce

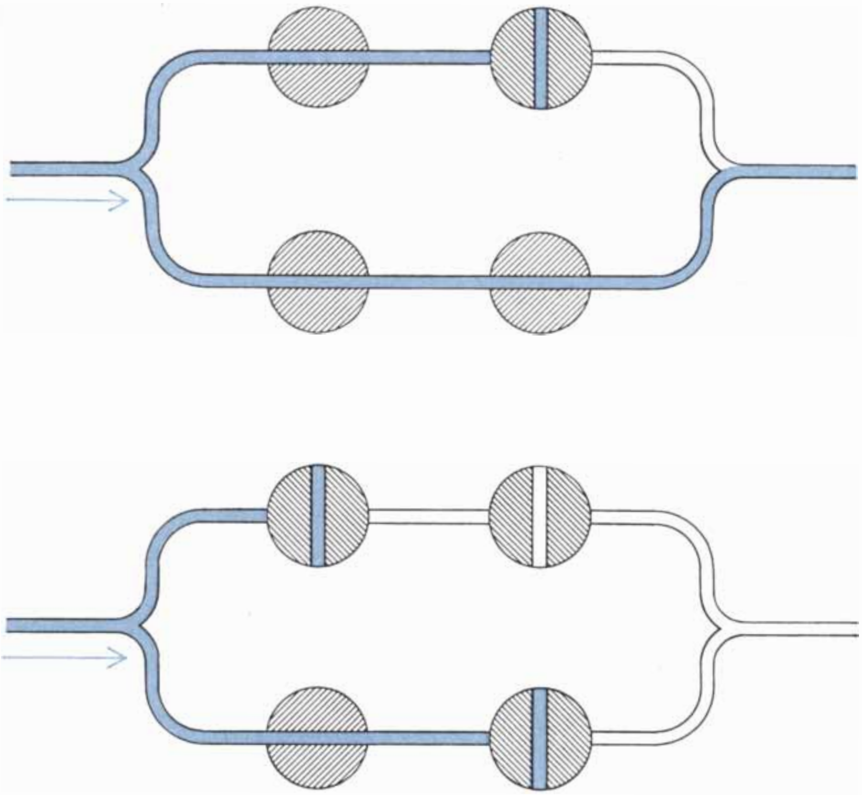
One of the difficult problems facing the engineer in an imperfect world is how to get reliable performance from complex electrical systems such as computers, in which any of perhaps a million things can go wrong. The traditional way to make a system more reliable is to improve the reliability of each of its parts, but in many cases component reliability has been pushed so close to its limits that further improvement may be uneconomical or even impossible. An alternative is available: to design a system so that it functions properly even when some of its parts fail. To accomplish this one must provide redundant, or extra, parts that are required to overcome errors but that would be quite unnecessary if no errors ever occurred. Techniques for inserting such redundancy have been developed in the past 10 years. This article will discuss some of these techniques and some recently discovered mathematical laws describing their effectiveness.

The most compelling reason for the current interest in redundancy theory and techniques is that modern technology is increasingly dependent on the reliability of complex electrical equipment, much of it involving digital computing machinery; the survival of an orbiting astronaut, for example, depends on the rapid and accurate calculation of arithmetical problems on digital computers. Moreover, the development of redundancy techniques for engineering man-made systems seems likely to lead to new insights into the arrangements evolved by nature to control errors in biological nervous systems. Redundancy theory, finally, presents an intellectual challenge rather closely related to that of its sister field, information theory.

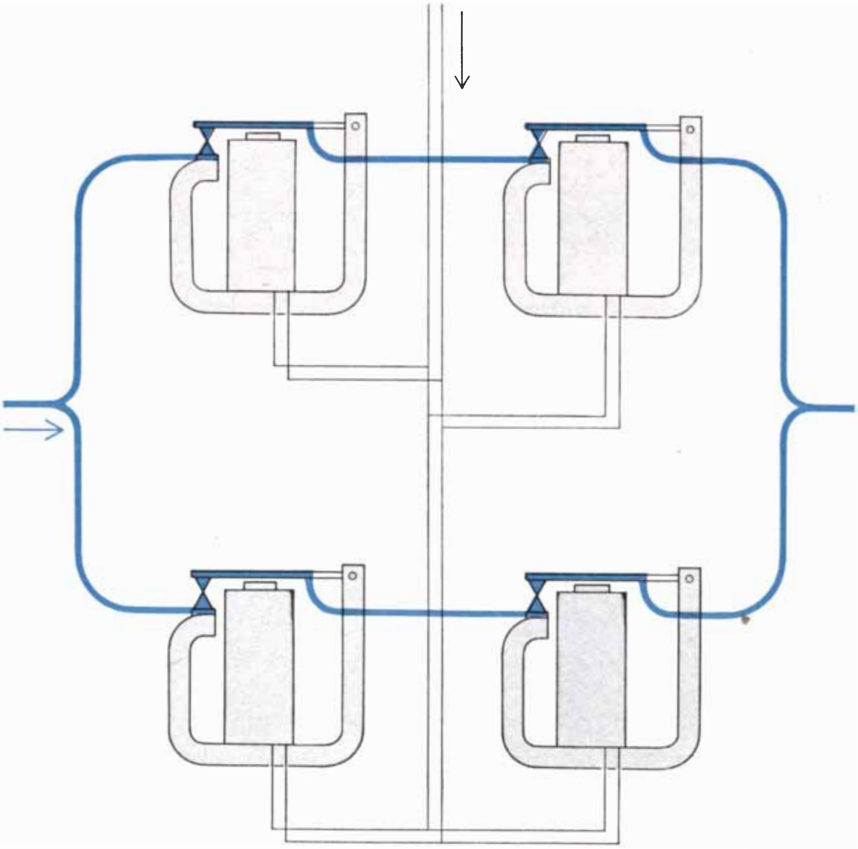
Parts fail at random and in unpredictable combinations, but these failures are subject to mathematical analysis on a statistical basis. The great power of the statistical treatment of engineering problems was first realized during World War II, when it was applied to such tasks as discriminating electrical signals from noise, and led to improvements in radar and similar systems. Soon it was seen that statistics could be applied to the analysis of engineering possibilities. In a classic paper published in 1948, Claude E. Shannon, then of the Bell Telephone Laboratories, showed that statistical techniques could even be used to study a piece of hardware that had not yet been invented and to predict both its potentialities and its limitations. He did this by defining mathematically the concept of "information" and finding theorems stating how much information can ever be extracted from data of given reliability. One might say that whereas information theory deals with



DEMONSTRATION MODEL built at the Westinghouse Defense and Space Center in Baltimore illustrates the effectiveness of redundancy. A visitor is invited to snip a substantial number of wires at random; the demonstrator continues to function reliably. This photograph shows four of the six banks of circuit cards that make up the demonstrator. There are two different types of cards. One type (*exemplified by card at top left corner*) carries the components of the "vote-taker" restoring organs that suppress error. Most of the components that perform the logical operations are on the other cards (*such as the one second from right in top row*).



WATER SYSTEM illustrates the principle of redundancy. If four petcocks take the place of one, any single error is nullified. In the top drawing water flows from left to right in spite of the fact that the valve at upper right is stuck closed; in the bottom drawing water does not flow when it should not, even though the valve at lower left is improperly open.



RELAY SYSTEM is directly analogous with the water system at the top of the page. When the electromagnets are energized, the four pairs of contact points close and electricity flows. With four relays, one can be improperly open or closed; the system will still work properly.

the manipulation of unreliable information with circuits assumed to be reliable, redundancy theory faces up to the handling of unreliable information with unreliable circuits.

Redundancy techniques are particularly well adapted to computer circuits in which the signals are binary, as they are in all commercial digital computers. A binary signal is one that has two possible physical conditions: either zero volts or one volt, typically (and in all examples given in this article). Circuits manipulating these binary voltages to produce other binary voltages can perform any arithmetical operation. One of the simplest binary devices is the relay, in which the two conditions are closed or open, "on" or "off." Relays have been basic components of telephone switching systems for years, and in the late 1930's it was relay computers that demonstrated the feasibility of automatic electrical computation. When the first modern electronic computers were built in the late 1940's, they were put together, with tubes and other radio parts dating from the 1920's, by people thinking in terms of relays.

It is easy to add redundancy to a relay circuit. Consider, by way of analogy, a water-flow system with four unreliable valves that are all opened or closed together [*see top illustration at left*]. One valve can be faulty in that it does not open or close when it should, and still the water will flow when it should and will not flow when it should not. The same thing happens with electrical current in a redundant relay system such as the one illustrated at the bottom of this page, which will function properly even if one relay fails. Although this system illustrates the principle of redundancy, and although some redundancy techniques are extensive generalizations of just such simple arrangements, for the most part what works for relays is not appropriate for electronic tubes and transistors. Before considering the techniques that are applicable to computers, let us consider the mathematical reasoning that shows just how effective redundancy can be against the unrelated, random failures that are so hard to eliminate from large electrical machines.

The effectiveness of redundancy when failures are unrelated derives from an important property of "statistically independent," or unrelated, events: The probability that several statistically independent events will all occur is the product of the probabilities that each of the events will occur. For example, if the probability that it will rain while you drive home from work is one in 10 (10^{-1}), the probability of having a flat tire on the way is one in 100 (10^{-2}) and the probability that you will get a toothache during the trip is one in 1,000 (10^{-3}), then the probability that all these events will occur is $10^{-1} \times 10^{-2} \times 10^{-3}$, or 10^{-6} (one in a million). In other words, it would be an extremely rare bit of bad luck.

In many redundancy techniques the number of extra circuits can be increased indefinitely to make the probability of failure as small as one wants—or as small as the customer is willing to pay for. The laws governing the relation between the number of extra circuits and a computer's failure probability depend essentially on the product rule of probabilities for independent events. The exact formulas for the relevant probabilities are complicated, as are similar formulas for the probabilities that arise in information theory. In both cases, however, the complicated expressions can often be accurately approximated by simple functions that are "asymptotic" to them. By way of illustration, consider the factorial function $n!$, or $1 \times 2 \times 3 \ldots \times n$. Its logarithm is well approximated, when n is at least 100, by the simple formula $n(-.435 + \log n)$. The approximation becomes better—its ratio to the exact expression comes closer to 1—as n becomes larger. Any such approximation is called an asymptote.

In the complicated probability calculations of redundancy theory one often deals with probabilities that are the sums of individual products of probabilities. For example, the probability that a coin flipped $3n$ times will come up heads on two-thirds or more of these occasions is the probability that the number of heads will be $2n$ plus the probability that it will be $2n + 1$ and so on up to $3n$. Each term in this sum contains a product of probabilities, and the sum of these probabilities has, for a large n, an asymptote that also contains a product of probabilities. Workers interested in both information theory and the newer field of redundancy theory have discovered asymptotes for probabilities that are sums of other probabilities, and with them they have established a number of fundamental theorems.

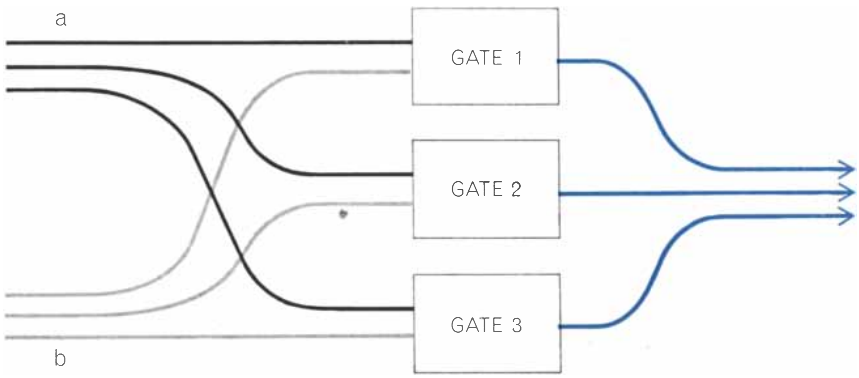
One such theorem, which has been discovered only recently, predicts that the probability of failure in a redundant system can decrease exponentially as the redundancy is increased. The theorem applies to a system that will fail only if at least a fraction B of its redundant parts should fail. If each part fails independently with some probability less than B, the failure probability of the system as a whole can be divided by two if one adds a specific number of redundant parts. The number depends on the failure probability of the individual parts and on the fraction B. And its dependence on B, interestingly enough, is the same kind of mathematical expression as the term for "information" in information theory. The important implication of this theorem is that the redundancy—and the cost—will go up only arithmetically, whereas the failure probability goes down geometrically.

A second theorem states that in a system with many different functions performed by parts of varying cost and reliability, it is generally better to add redundancy in order to give each function the same probability of failure, regardless of the relative cost of the parts. In other words, it is generally best to allocate costs in order to improve the strength of the weakest link in the chain, even when it costs more to strengthen some links than others. Finally, the product rule for independent probabilities indicates that as larger and larger computers are built, relatively little of the additional expense will be required to maintain reliability through redundancy.

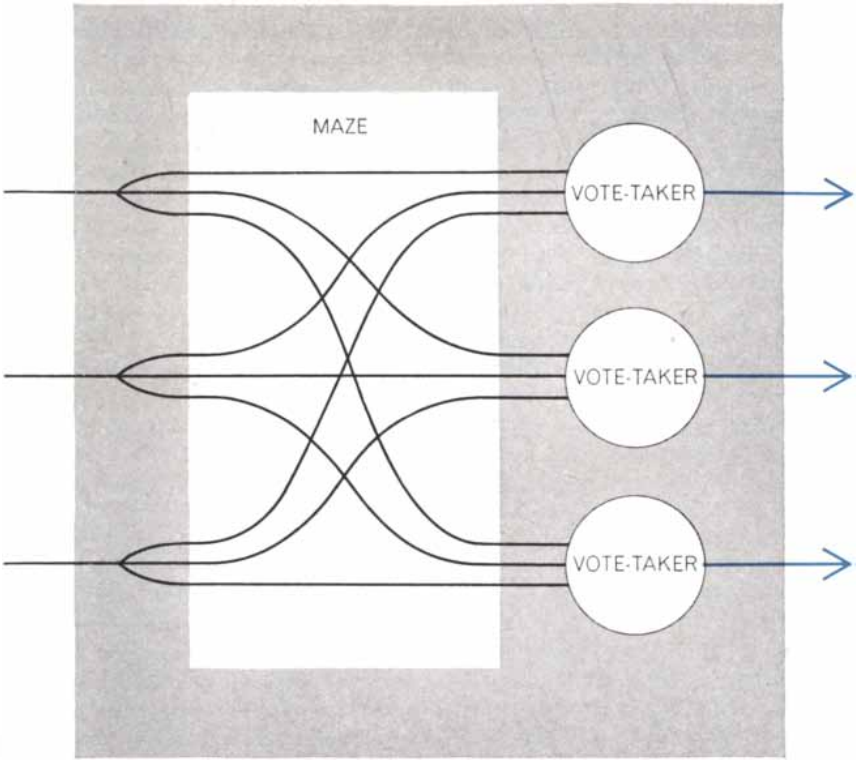
These, at least, are the theoretical predictions. A number of practical problems can prevent their fulfillment, notably the difficulty of seeing to it that the failures are indeed random and independent of one another. Redundancy does no good, and can even do harm, if the various parts of a circuit are not isolated so that a local failure cannot cause damage to nearby parts. In devising redundancy techniques an engineer must therefore understand and keep in mind the physical implications of his mathematical models and his theorems.

One of the first systematic redundancy techniques to be discovered is based on the replacement of an individual wire by a bundle of wires, each of which, in the absence of error, carries the same signal. It is as though there were a nation in which no citizen could be trusted, and accordingly several citizens were required to act together in making decisions, executing orders or delivering messages. As a simple example of the bundle idea consider a part of a nonredundant computer that is required to have a binary output (c) of one volt if one input (a) is one volt and the other (b) is zero. A two-input, one-output logic gate, or electrical circuit, can be made with this property [*see illustration below*]. In a redundant version of this circuit each wire is replaced by a bundle of wires and the logic gate is replaced by several independent but identical gates. (The number of wires in each bundle and the number of gates is three in the illustration, but it could be any odd number.) Such a redundant scheme is incomplete, however, because the information on the redundant wires of the output bundle has not been made to interact. The circuit still requires some modification that will interconnect the components and suppress errors.

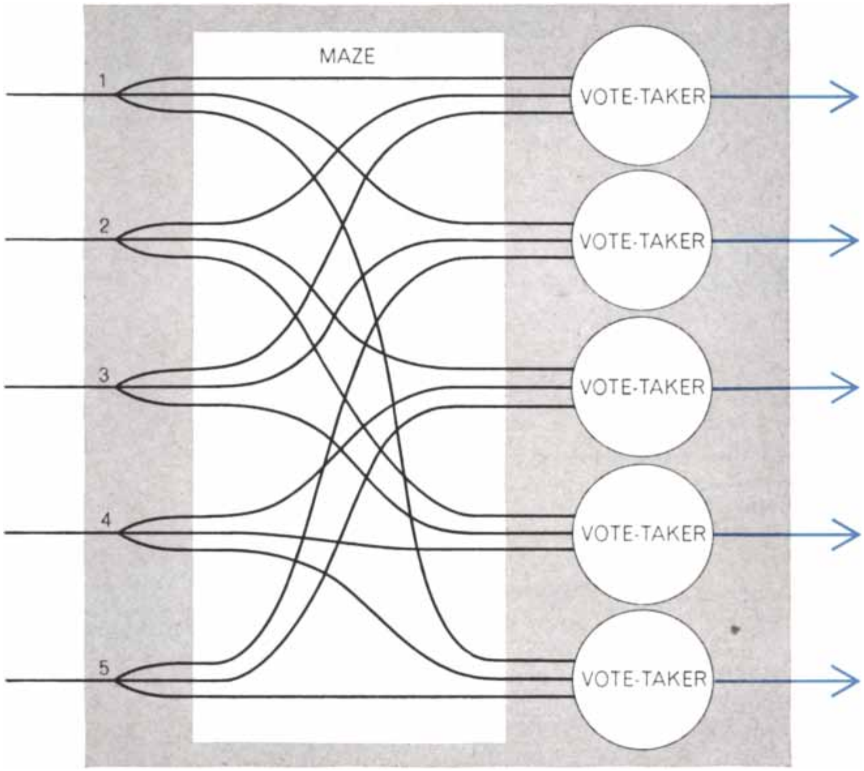
The device that does this is a "restoring organ," which receives as inputs the several wires of a bundle, allows their redundant information to interact and thereby produces an output bundle that contains a more reliable version of



BUNDLE CONCEPT is basic in redundancy. Assume that the simple circuit shown at the top is to be made redundant; it is a circuit that puts out a one-volt signal if input *a* is one volt and input *b* is zero. In the redundant version below, each input and output wire is replaced by a bundle of three wires and there are three logic gates rather than one.



RESTORING ORGAN causes the several wires of a bundle to interact and so to produce a more reliable bundle. This type depends on "vote-takers" to create the output bundle (*color*). In this example each vote-taker receives an input from each wire of the bundle. A "majority vote" (two out of three here) determines the output, correcting any single error.



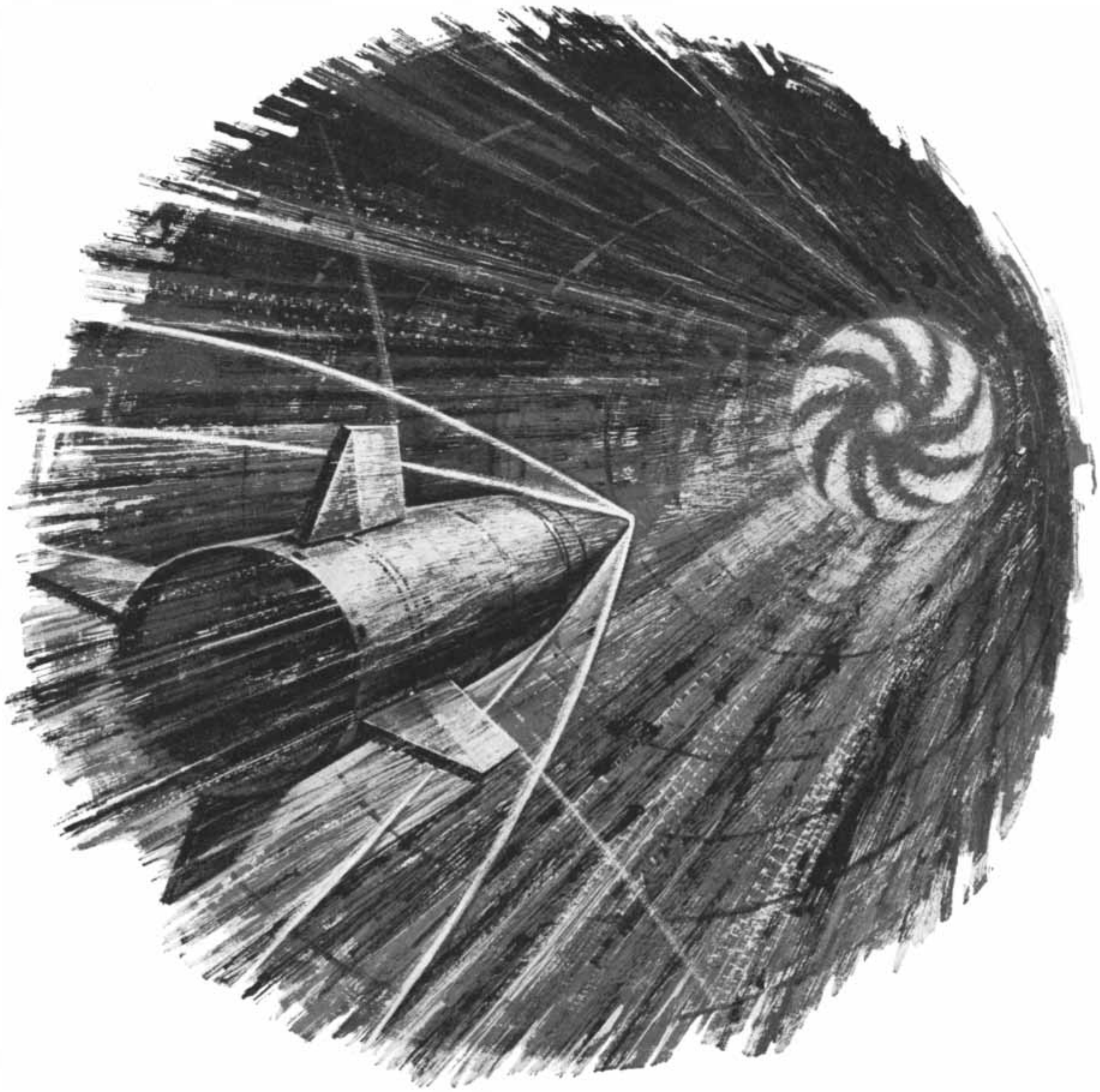
MAZE becomes important if the inputs to each vote-taker must be fewer than the number of vote-takers. In this restoring organ each vote-taker receives a signal from only three of the five input wires. The inputs could simply be connected haphazardly in a "random maze." Or, as in this example, the connections can be worked out in a "deterministic maze" designed to reduce the number of double errors that can get through the restoring organ.

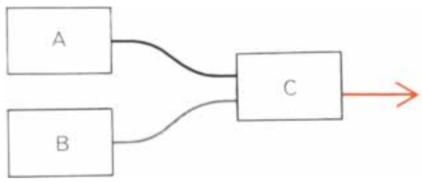
the input signal. In one type of restoring organ [*see illustration at left*] the signal on each output line is obtained by a "vote-taker," a logic circuit that can take a majority vote of its inputs. If two or three of its inputs are one-volt signals, the output will be one volt; otherwise it will be zero. A restoring organ of this type can correct any single error. If perfectly reliable vote-takers were available, only one of them would be needed in a restoring organ. Because they are fallible, however, a separate one is used for each output. A mistake by one vote-taker is no more harmful than an error in the unreliable circuit carrying that vote-taker's output.

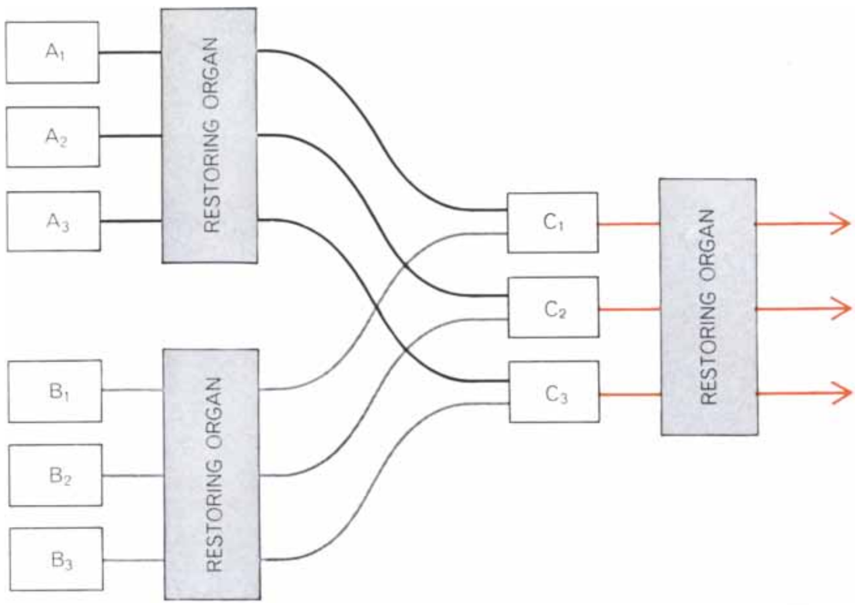
Clearly vote-taking could be a great deal more effective if the various inputs had an influence proportional to their degree of reliability—an aristocratic rather than a democratic suffrage, as it were. This can be accomplished by giving the inputs unequal weights; the output is the signal "voted for" by the greater sum of weights rather than simply by the larger number of inputs. The beauty of such a vote-taker is that it can compute the correct output from a single reliable input, even in the face of a large number of contradictory, unreliable inputs.

In order to weight the votes properly, self-adjusting, or "adaptive," circuits are added to the vote-taker to adjust each input's vote-weight in accordance with its reliability. The error probability of each input can be estimated from the number of times the input disagrees with a special "training" answer supplied during a check program run from time to time for this purpose. Alternatively, the reliability of each input can be found by continually counting the disagreements between that input and the output of the vote-taker itself. In this way, by a kind of feedback of information, each input's weight is continually adjusted in accordance with its recent reliability.

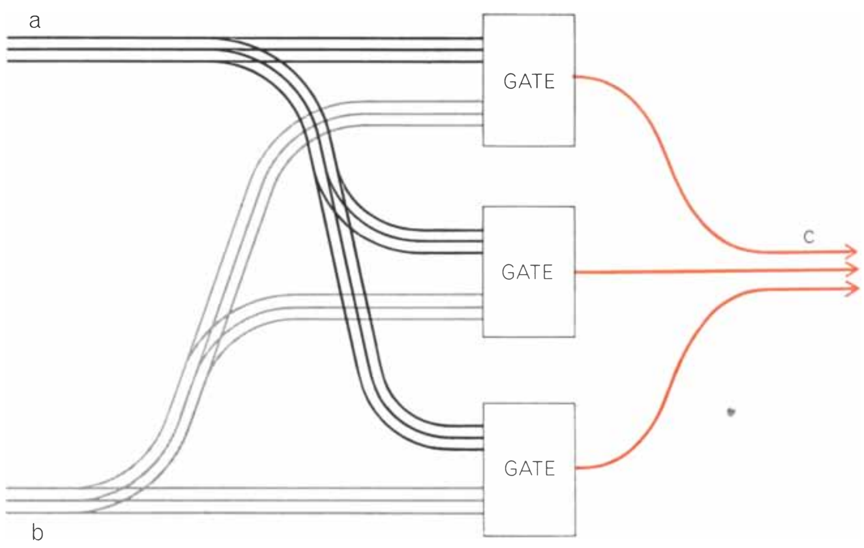
Restoring organs can be constructed in a number of ways. Circuit constraints, for instance, might make it necessary to limit the number of inputs to a vote-taker to three when reliability considerations dictate a redundancy of five. The restoring organ will be composed of five three-input vote-takers. Each vote-taker cannot receive all input lines, and the problem arises of deciding which inputs to assign to which vote-taker. One solution is simply to avoid the decision: to allow a "random maze" to establish the connections. At first thought the idea of placing a







REDUNDANT CIRCUIT is constructed by combining logic elements and restoring organs. A nonredundant circuit (*top*) includes logic gates *A* and *B*, which feed their output to gate *C* for processing. In the redundant version (*bottom*) each gate becomes three gates, each wire a bundle of three, and restoring organs are inserted after each logical operation.



THRESHOLD GATE can perform digital logic and error correction simultaneously. If each wire in the *c* bundle is to carry one volt when the signals on the *a* or the *b* bundle are one volt, the *c* signal can be synthesized by threshold gates as illustrated. Each threshold gate has six excitatory inputs and has an output of one volt only when at least two of its inputs are one volt; that is, it has a threshold of two. Additional restoring organs are unnecessary.

randomly wired circuit in an intricate computer may seem about as sensible as expecting a blindfolded pigeon to write a poem by pecking at typewriter keys, but on statistical analysis it makes sense. The reasoning goes like this: Even without knowing which is the best maze to use, one can at least analyze the properties of a random maze and see how reliable it is. If the average random maze performs successfully, use it. Or, knowing how reliable a random maze is, try to design a systematic one that is better than average.

Recently a few systematic mazes have been worked out that are definitely better than random mazes. In a restoring organ with one of these deterministic mazes any single error will, as in simpler restoring organs, be corrected by all the vote-takers it enters [*see bottom illustration on page 106*]. As a result of the particular pattern of connections, some double errors, such as an error on both line 1 and line 2, will be reduced to single errors, which can be corrected by the next restoring organ. Other double errors, however—on lines 1 and 3, for instance—will still be double errors when they emerge from this restoring organ. This does not mean that there is no hope of correcting all double errors. It turns out that of the 10 possible double errors that can enter this organ, only five will produce double output errors. It is possible to arrange the connections in such a way that the five double errors emerge in exactly those positions that will be reduced to single errors in the next restoring organ. By using similar restoring organs throughout a computer one can therefore eliminate all double errors.

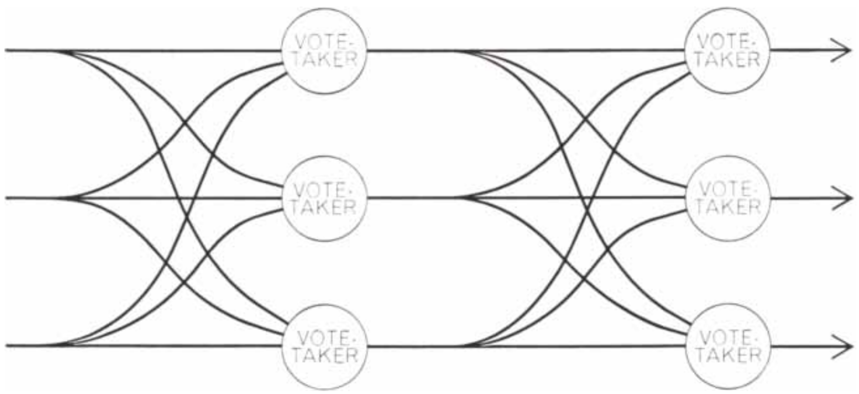
A redundancy theory based on restoring organs is elegant and satisfying, but it does have some weaknesses. For one thing, a redundancy theory truly applicable to biological nervous systems ought to have more homogeneity in its circuits, namely fewer different kinds of components. Moreover, if the theory is to be optimum in an engineering sense, the restoring organ should be made to do more useful computation. In brief, one would like a more generalized theory that offers homogeneity to the biologist and efficiency to the engineer.

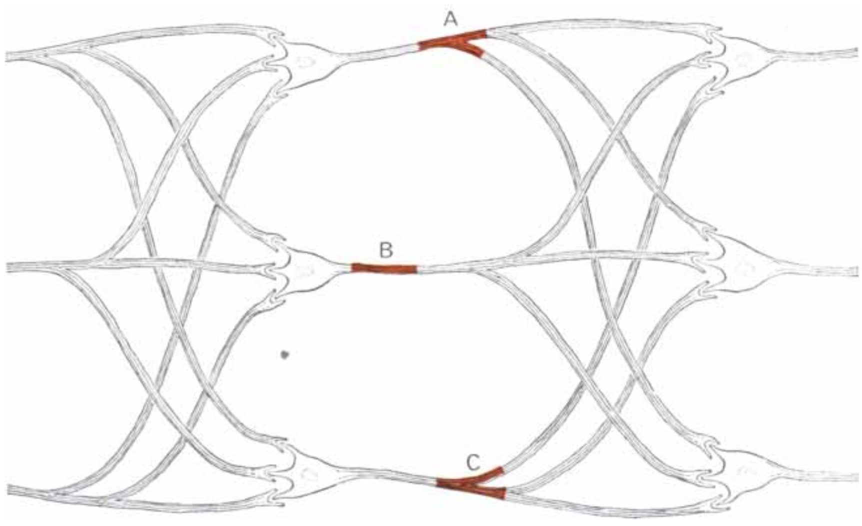
Both of these objectives are served by a theory in which error correction and the execution of digital logic are combined in a single logic gate. One type of circuit with which this can be accomplished is a "threshold gate." This is a gate that is "excited," or has an output other than zero, only if the num-

ber of excitatory inputs minus the number of inhibitory inputs equals or exceeds a threshold level. Suppose, for example, that an output of one is desired if either input a or input b or both is one. This can be done by a threshold-gate circuit in which a and b are excitatory and the threshold is one. The operation can be made redundant if three six-input threshold gates are substituted. Three of the six inputs to each are independent versions of a and three are versions of b, and the threshold is set at two [*see bottom illustration on page 108*]. Threshold gates and several other types of gate can be arranged in a network in which redundant signals are interwoven much as they are in the input mazes of restoring organs.

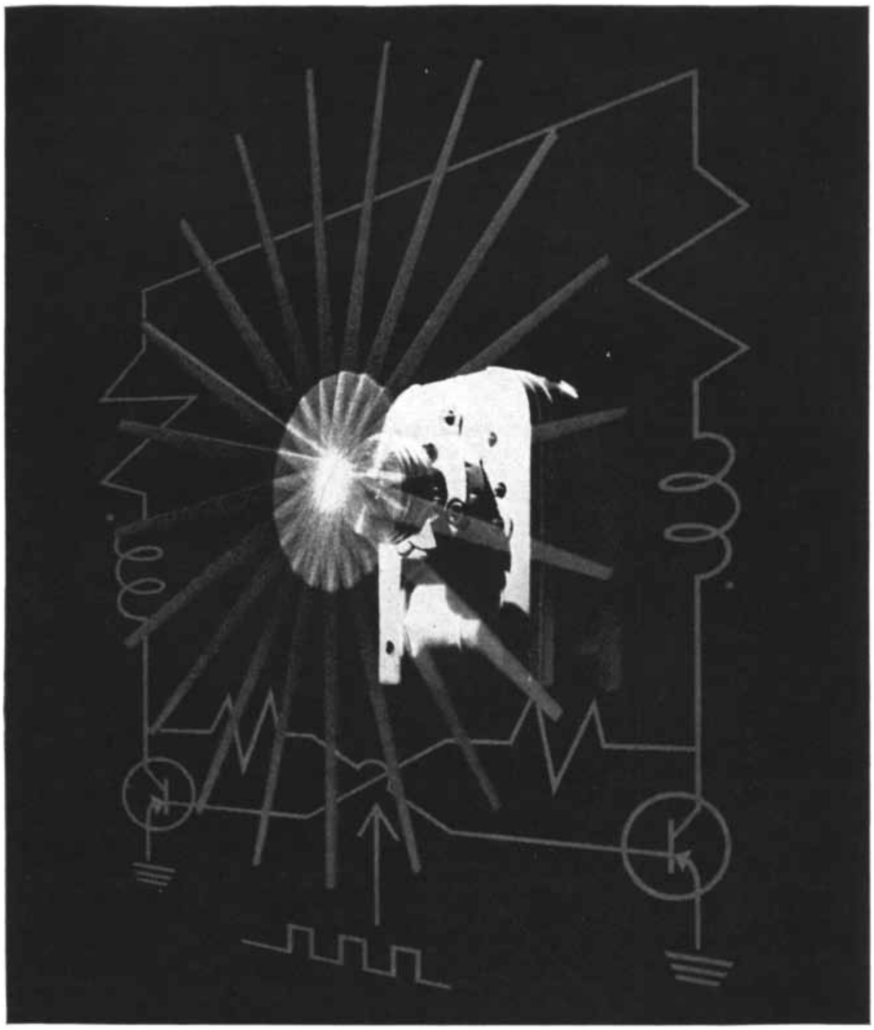
The nervous systems of higher animals, including man, can sustain local injuries without showing any detectable sign of damage. This fact and the observation that most neurons, or nerve cells, receive inputs from more than one other neuron suggest that biological nervous systems must have considerable redundancy. The general theory of interwoven, redundant logic has developed to the point where it is possible to speculate on how redundant neurons work.

If two sets of three-input vote-takers are placed end to end [*see illustration below*], a single input wire or vote-taker can fail and the output bundle will still have a correct majority. A majority-rule vote-taker can be thought of as a threshold gate in which the threshold is equal to half the number of inputs. Biological neurons behave as just such gates, firing when the number of excitatory inputs minus the number of inhibitory inputs equals or exceeds the neuron's threshold. When the neuron fires, a nerve impulse—a traveling discharge of electrical energy—propagates down the long, slender axon and affects another neuron, apparently by injecting into it a chemical substance that either stimulates it to fire (excitatory input) or prevents it from firing (inhibitory input). A simple





BIOLOGICAL NEURONS are like vote-takers that fire if the number of excitatory inputs minus the inhibitory ones exceeds a threshold. In the vote-taker series (*top*) one signal can be wrong and the output bundle will still be correct. In the biological version (*bottom*) neurons with a threshold of two replace vote-takers and axons replace wires. Nerve impulse *B* is delayed but *A* and *C* will reach all three neurons at the right on time and trigger them.



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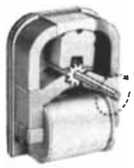

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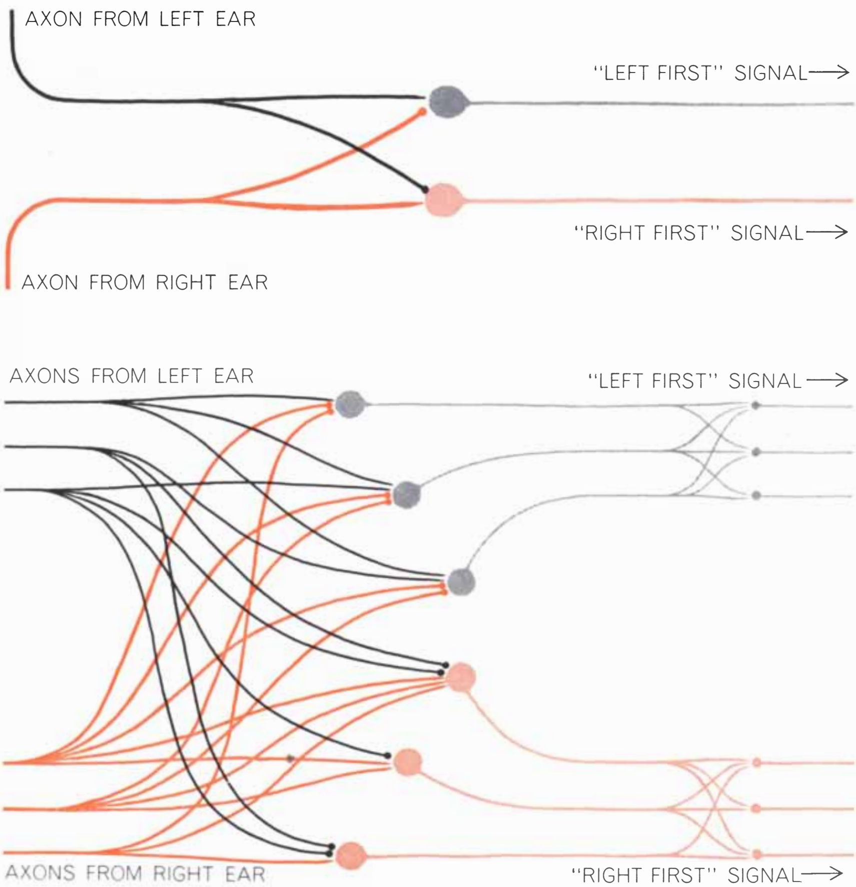
network that would be the biological version of a chain of two restoring organs might be arranged as in the illustration on page 110. One neuron could fail, or the signal in one axon could be delayed, and the "bundle" of axons would still carry the correct signals.

Actual neuron networks are, to be sure, a great deal more complicated, but the basic principles of redundancy seem applicable still. The illustration below, for example, shows a neuron model that might explain a person's ability to localize sound by distinguishing which ear receives a sound wave first. It seems likely that there are two kinds of neuron involved. One kind is stimulated by a signal from the right ear and inhibited by a signal from the left; the other is stimulated by a signal from the left ear and inhibited by one from the right. The thresholds are such that the neurons fire only if the stimulating impulse arrives first. One neuron is therefore a "left first" receptor and the other a "right first" receptor. In a redundant version of such a system each signal is carried by several axons, so that none is indispensable. The neurons have somewhat random connections, some of them receiving more axons than others, but each has the appropriate excitatory or inhibitory connections. A "restoring organ" of neurons follows each set of three neurons that makes the decisions as to which ear received the sound first. This restoring organ tends to emphasize the decision of the majority and suppress the decision of the minority.

The richly redundant networks of biological nervous systems must have capabilities beyond anything our theories can yet explain. For example, there is probably a considerable degree of flexibility in biological networks that allows redundant circuits to improve reliability when errors are common and leaves them free to improve the organism's over-all nervous capability when errors are infrequent. No one, however, has yet suggested a plausible scheme for such self-organization.



NERVOUS SYSTEMS apparently are richly redundant. This example shows a hypothetical arrangement of nerve cells for localizing sound (*top*). In it signals from each ear are assumed to be excitatory (*pointed*) for one kind of neuron and inhibitory (*rounded*) for another. In a redundant version of this model (*bottom*) three axons from each ear branch at random to the neurons that make the "right first" or "left first" decision. Notice that a "restoring organ" of three other neurons follows the "logic" neurons and tends to suppress errors.

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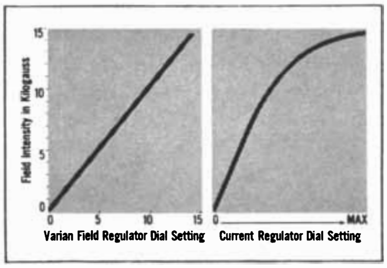

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THE BLACK DEATH

The plague that killed a quarter of the people of Europe in the years 1348–1350 is still studied to shed light on human behavior under conditions of universal catastrophe

by William L. Langer

In the three years from 1348 through 1350 the pandemic of plague known as the Black Death, or, as the Germans called it, the Great Dying, killed at least a fourth of the population of Europe. It was undoubtedly the worst disaster that has ever befallen mankind. Today we can have no real conception of the terror under which people lived in the shadow of the plague. For more than two centuries plague has not been a serious threat to mankind in the large, although it is still a grisly presence in parts of the Far East and Africa. Scholars continue to study the Great Dying, however, as a historic example of human behavior under the stress of universal catastrophe. In these days when the threat of plague has been replaced by the threat of mass human extermination by even more rapid means, there has been a sharp renewal of interest in the history of the 14th-century calamity. With new perspective, students are investigating its manifold effects: demographic, economic, psychological, moral and religious.

Plague is now recognized as a well-marked disease caused by a specific organism (*Bacillus pestis*). It is known in three forms, all highly fatal: pneumonic (attacking primarily the lungs), bubonic (producing buboes, or swellings, of the lymph glands) and septicemic (killing the victim rapidly by poisoning of the blood). The disease is transmitted to man by fleas, mainly from black rats and certain other rodents, including ground squirrels. It produces high fever, agonizing pain and prostration, and it is usually fatal within five or six days. The Black Death got its name from dark blotches produced by hemorrhages in the skin.

There had been outbreaks of plague in the Roman Empire in the sixth century and in North Africa earlier, but for some reason epidemics of the disease in Europe were comparatively rare after that until the 14th century. Some historians have suggested that the black rat was first brought to western Europe during the Crusades by expeditions returning from the Middle East. This seems unlikely: remains of the rat have been found in prehistoric sites in Switzerland, and in all probability the houses of Europe were infested with rats throughout the Middle Ages.

In any event, the 14th-century pandemic clearly began in 1348 in the ports of Italy, apparently brought in by merchant ships from Black Sea ports. It gradually spread through Italy and in the next two years swept across Spain, France, England, central Europe and Scandinavia. It advanced slowly but pitilessly, striking with deadliest effect in the crowded, unsanitary towns. Each year the epidemic rose to a peak in the late summer, when the fleas were most abundant, and subsided during the winter, only to break out anew in the spring.

The pandemic of 1348–1350 was followed by a long series of recurrent outbreaks all over Europe, coming at intervals of 10 years or less. In London there were at least 20 attacks of plague in the 15th century, and in Venice the Black Death struck 23 times between 1348 and 1576. The plague epidemics were frequently accompanied by severe outbreaks of typhus, syphilis and "English sweat"—apparently a deadly form of influenza that repeatedly afflicted not only England but also continental Europe in the first half of the 16th century.

From the 13th to the late 17th century Europe was disease-ridden as never before or since. In England the long affliction came to a climax with an epidemic of bubonic plague in 1665 that killed nearly a tenth of London's estimated population of 460,000, two-thirds of whom fled the city during the outbreak. Thereafter in western and central Europe the plague rapidly died away as mysteriously as it had come. The theories advanced to explain its subsidence are as unconvincing as those given for its rise. It was long supposed, for instance, that an invasion of Europe early in the 18th century by brown rats, which killed off the smaller black rats, was responsible for the decline of the disease. This can hardly be the reason; the plague had begun to subside decades before, and the brown rat did not by any means exterminate the black rat. More probably the answer must be sought in something that happened to the flea, the bacillus or the living conditions of the human host.

This article, however, is concerned not with the medical but with the social aspects of the Black Death. Let us begin by examining the dimensions of the catastrophe in terms of the death toll.

As reported by chroniclers of the time, the mortality figures were so incredibly high that modern scholars long regarded them with skepticism. Recent detailed and rigorously conducted analyses indicate, however, that many of the reports were substantially correct. It is now generally accepted that at least a quarter of the European population was wiped out in the first epidemic of 1348 through 1350, and that in the next 50 years the total mortality rose to more than a third of the population. The incidence of the disease and the mortality rate varied, of course, from place to place. Florence was reduced in population from 90,000 to 45,000, Siena from 42,000 to 15,000; Hamburg apparently lost almost two-thirds of its inhabitants. These estimates are borne out by accurate records that were kept in later epidemics. In Venice, for example, the Magistrato della Sanità (board of health) kept a meticulous count of the victims of a severe plague attack in 1576 and 1577; the deaths totaled 46,721 in a total estimated population of about 160,000. In 1720 Marseilles lost 40,000 of a population of 90,000, and in Messina about half of the inhabitants died in 1743.

It is now estimated that the total population of England fell from about 3.8 million to 2.1 million in the period from 1348 to 1374. In France, where the loss of life was increased by the Hundred Years' War, the fall in population was even more precipitate. In western and central Europe as a whole the mortality was so great that it took nearly two centuries for the population level of 1348 to be regained.

The Black Death was a scourge such as man had never known. Eighty per cent or more of those who came down with the plague died within two or three days, usually in agonizing pain. No one knew the cause of or any preventive or cure for the disease. The medical profession was all but helpless, and the desperate measures taken by town authorities proved largely futile. It is difficult to imagine the growing terror with which the people must have watched the inexorable advance of the disease on their community.

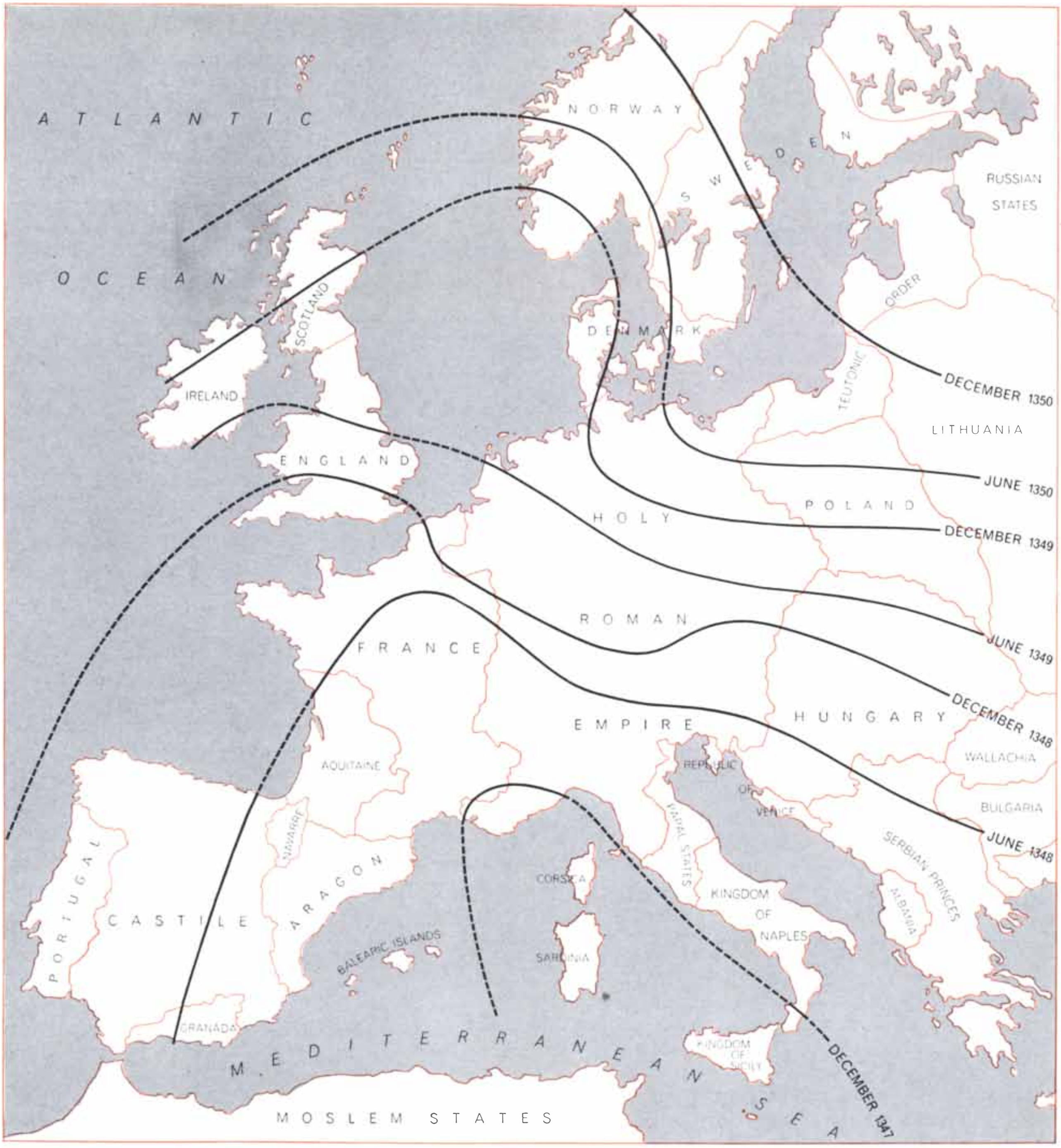
They responded in various ways. Almost everyone, in that medieval time, interpreted the plague as a punishment by God for human sins, but there were arguments whether the Deity was sending retribution through the poisoned arrows of evil angels, "venomous moleculae" or earthquake-induced or comet-borne miasmas. Many blamed the Jews, accusing them of poisoning the wells or otherwise acting as agents of Satan. People crowded into the churches, appealing for protection to the Virgin, to St. Sebastian, to St. Roch or to any of 60 other saints believed to have special influence against the disease. In the streets half-naked flagellants, members of the century-old cult of flagellantism, marched in processions whipping each other and warning the people to purge themselves of their sins before the coming day of atonement.

Flight in the face of approaching danger has always been a fundamental human reaction, in modern as well as ancient times. As recently as 1830, 60,000 people fled from Moscow during an epidemic of cholera, and two years later, when the first cases of this disease turned up in New York City, fully a fourth of the population of 220,000 took flight in

RAPHAEL'S "LA PÈSTE" ("The Plague") reflects the preoccupation of European art with plague and its consequences during the plague-ridden three centuries following the Black Death. This picture, now worn with time, is divided into two parts: night at right and day at left. Among other plague themes of artists were the dance of death and the terrors of the Last Judgment.

steamboats, stagecoaches, carts and even wheelbarrows. The plague epidemics of the 14th to 16th century of course produced even more frightened mass migrations from the towns. Emperors, kings, princes, the clergy, merchants, lawyers, professors, students, judges and even physicians rushed away, leaving the common people to shift for themselves. All who could get away shut themselves up in houses in the country.

At the same time drastic efforts were made to segregate those who were forced to remain in the towns. In an epidemic in 1563 Queen Elizabeth took refuge in Windsor Castle and had a gallows erected on which to hang anyone who had the temerity to come out to Windsor from plague-ridden London. Often when a town was hit by the plague a cordon of troops would be thrown around the town to isolate it, allowing no one to leave or enter. In the afflicted cities entire streets were closed off by chains, the sick were quarantined in their houses and gallows were installed in the public squares as a warning against the violation of regulations. The French surgeon Ambroise Paré, writing of a plague epidemic in 1568,



APPROXIMATE CHRONOLOGY of the Black Death's rapid sweep through Europe in the middle of the 14th century is indicated on this map, which shows the political divisions as they existed at the time. The plague, which was apparently brought from Asia by ships, obtained a European foothold in the Mediterranean in 1347; during the succeeding three years only a few small areas escaped.

reported that husbands and wives deserted each other, that parents sometimes even abandoned their children and that people went mad with terror and committed suicide.

Victims of the disease often died in the streets, as is shown in Raphael's "La Pèste," now in the Uffizi Gallery in Florence. Gravediggers were understandably scarce. For the most part those hired for the job, at fantastic wages, were criminals and tramps—men who could not be expected to draw fine distinctions between the dying and the dead. The corpses and the near corpses were thrown into carts and dumped indiscriminately into huge pits outside the town walls.

The sufferings and reactions of humanity when the plague came have been depicted vividly by writers such as Boccaccio, Daniel Defoe, Alessandro Manzoni and the late Albert Camus (in his novel *The Plague*) and by artists from Raphael and Holbein to Delacroix. Boccaccio's *Decameron,* an account of a group of well-to-do cavaliers and maidens who shut themselves up in a country house during the Black Death in Florence and sought to distract themselves with revelry and spicy stories, illustrates one of the characteristic responses of mankind to fear and impending disaster. It was most simply described by Thucydides in his report of the "Plague of Athens" in 430 B.C.:

"Men resolved to get out of life the pleasures which could be had speedily and would satisfy their lusts, regarding their bodies and their wealth alike as transitory.... No fear of gods or law of men restrained them; for, on the one hand, seeing that all men were perishing alike, they judged that piety or impiety came to the same thing, and, on the other hand, no one expected that he would live to be called to account and pay the penalty for his misdeeds. On the contrary, they believed that the penalty already decreed against them and now hanging over their heads was a far heavier one, and that before it fell it was only reasonable to get some enjoyment out of life."

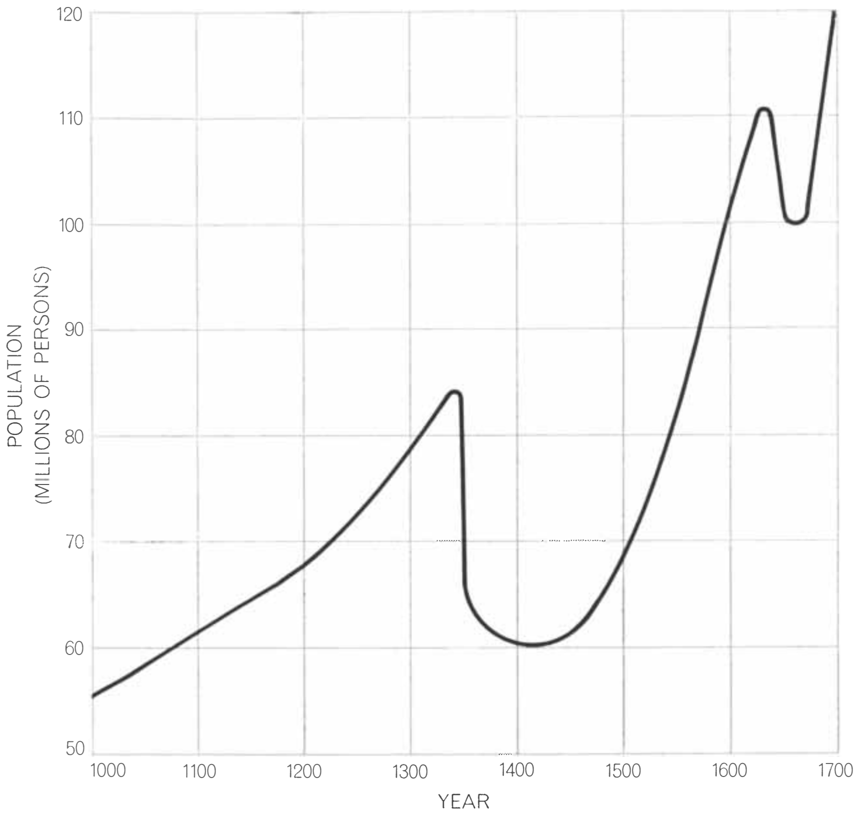
From this philosophy one might also develop the rationalization that hilarity and the liberal use of liquor could ward off the plague. In any event, many people of all classes gave themselves up to carousing and ribaldry. The Reformation theologian John Wycliffe, who survived the Black Death of the 14th century, wrote with dismay of the lawlessness and depravity of the time. Everywhere, wrote chroniclers of the epidemics in London then and later, there was "drinking, roaring and surfeiting.... In one house you might hear them roaring under the pangs of death, in the next tippling, whoring and belching out blasphemies against God." Even the sober Samuel Pepys admitted to his diary that he had made merry in the shadow of death, indulging himself and his wife in a "great store of dancings." The university town of Oxford, like London, also was the scene of much "lewd and dissolute behavior."

The outbreak of an epidemic of plague was almost invariably the signal for a wave of crime and violence. As Boccaccio wrote, "the reverend authority of the laws, both human and divine, was all in a manner dissolved and fallen into decay, for lack of the ministers and executors thereof." In the midst of death, looting and robbery flourished. Burial gangs looted the houses of the dead and stripped the corpses of anything of value before throwing them into the pits. On occasion they even murdered the sick.

Just as desperation drove some to a complete abandonment of morality, it drove others, perhaps the majority, to pathetic extravagances of religiosity or superstition. The poet George Wither noted this contrast in the London epidemic of 1625:

Some streets had Churches full
of people, weeping;
Some others, Tavernes had, rude-revell
keeping;
Within some houses Psalmes
and Hymnes were sung;
With raylings and loud scouldings
others rung.

Many people threw themselves on God's mercy, showered the church with gifts and made extravagant vows for the future. Others hunted down Jews and witches as the originators of the plague. The Black Death generated a startling spread of belief in witchcraft. Even as learned a scholar and theologian as John Calvin was convinced that a group of male and female witches, acting as agents of Satan, had brought the plague to Geneva. In the cult of Satanism, as in that of flagellantism, there was a strong strain of sexuality. It was believed that the women accused of being witches had intercourse with the



IMPACT ON POPULATION from recurrent plagues in Europe is indicated. For more than 300 years after 1347 the plagues checked the normal rise in population; sometimes, as in the 14th and 17th centuries, they resulted in sharp reductions. The figures shown on this chart derive from estimates by students of population; actual data for the period are scarce.

Devil and could strike men with sexual impotence. From the psychoanalytic point of view this belief may have stemmed from an unconscious reaction to the tremendous shrinkage of the population.

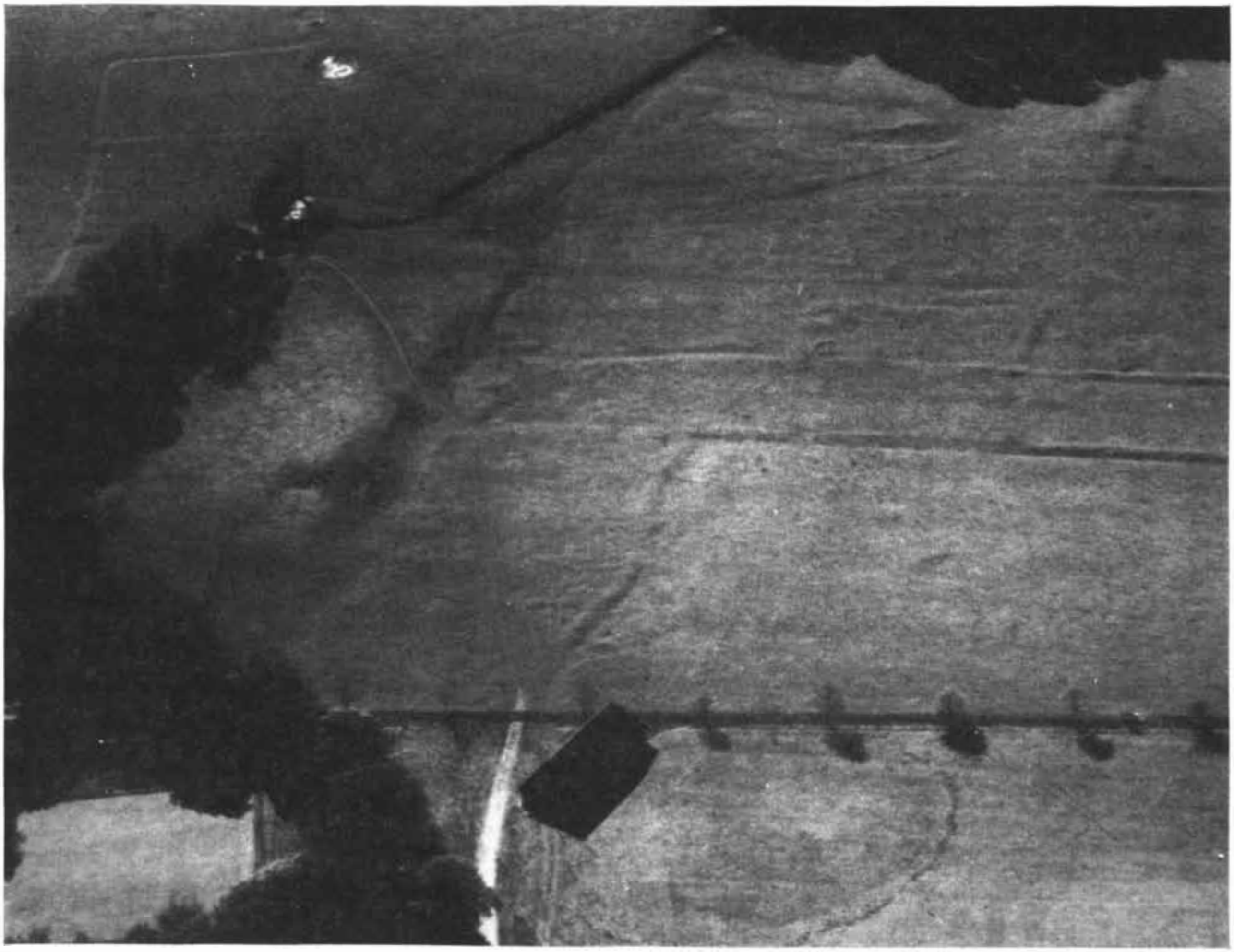
Jews and witches were not the only victims of the general panic. The wrath of the people also fell on physicians. They were accused of encouraging or helping the spread of the plague instead of checking it. Paré tells us that some of them were stoned in the streets in France. (In the 19th century physicians were similarly made scapegoats during epidemics of cholera. Some people accused them of poisoning public water supplies, at the behest of the rich, in order to kill off the excessive numbers of the poor.)

Although we have fairly accurate knowledge of the immediate effects of the great plagues in Europe—they were fully and circumstantially chronicled by many contemporary writers—it is not so easy to specify the long-term effects of the plagues. Many other factors entered into the shaping of Europe's history during and after the period of the plague epidemics. Nevertheless, there can be no doubt that the Great Dying had a profound and lasting influence on that history.

In its economic life Europe suffered a sudden and drastic change. Before the Black Death of 1348–1350 the Continent had enjoyed a period of rather rapid population growth, territorial expansion and general prosperity. After the pandemic Europe sank into a long depression: a century or more of economic stagnation and decline. The most serious disruption took place in agriculture.

For a short time the towns and cities experienced a flush of apparent prosperity. Many survivors of the epidemic had suddenly inherited substantial amounts of property and money from the wholesale departure of their relatives. They built elegant houses and went on a buying spree that made work (and high prices) for the manufacturing artisans. The churches and other public institutions, sharing in the wealth of the new rich, also built imposing and expensive structures.

The rural areas, on the other hand, virtually collapsed. With fewer people to feed in the towns and cities, the farmers lost a large part of the market for their crops. Grain prices fell precipitately. So did the farm population. Already sadly depleted by the ravages of the plague, it was now further reduced by a movement to the towns, which offered the impoverished farmers work as artisans. In spite of strenuous efforts by landlords and lords of the manor to keep the peasants on the land by law and sometimes by force, the rural population fled to the cities en masse. Thousands of farms and villages were deserted. In central Germany some 70



DESERTED ENGLISH VILLAGE, typical of many medieval communities made ghost towns by the Black Death and succeeding plagues, occupied the site shown in this aerial photograph. This site is Tusmore in Oxfordshire; most of the lines are earthworks that bounded farm enclosures behind cottages. Aerial photography has been used to locate many abandoned medieval villages.

Actual photograph of CRAB NEBULA

Light...from the edge of time

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per cent of all the farm settlements were abandoned in the period following the Black Death. (Many of these "lost" farms and villages, long overgrown, have recently been located by aerial photography.)

Farms became wilderness or pasture. Rents and land values disappeared. The minor land-owning gentry sank into poverty. In the words of the 14th-century poet Petrarch, "a vast and dreadful solitude" settled over the land. And of course in the long run the depression of agriculture engulfed the cities in depression as well.

Some authorities believe that Europe had begun to fall into a period of economic decay before the Black Death and that the epidemics only accentuated this trend. The question is certainly a complicated one. Wars and other economic forces no doubt played their part in Europe's long recession. It seems probable, however, that the decisive factor was the repeated onslaught of epidemics that depleted and weakened the population. The present consensus on the subject is that population change is a main cause of economic change rather than vice versa. Surely it must be considered significant that Europe's economic revival in the 17th and 18th centuries coincided with the disappearance of the plague and a burst of rapid population growth [see "Population," by Kingsley Davis; SCIENTIFIC AMERICAN, September, 1963].

The psychological effects of the ordeal of the plague are at least as impressive as the economic ones. For a long time it held all of Europe in an apocalyptic mood, which the Dutch historian Johan Huizinga analyzed brilliantly a generation ago in his study *The Waning of the Middle Ages*. As Arturo Castiglioni, the eminent Yale University historian of medicine, has written: "Fear was the sovereign ruler of this epoch." Men lived and worked in constant dread of disease and imminent death. "No thought is born in me that has not 'Death' engraved upon it," wrote Michelangelo.

Much of the art of the time reflected a macabre interest in graves and an almost pathological predilection for the manifestations of disease and putrefaction. Countless painters treated with almost loving detail the sufferings of Christ, the terrors of the Last Judgment and the tortures of Hell. Woodcuts and paintings depicting the dance of death, inspired directly by the Black Death, enjoyed a morbid popularity. With pitiless realism these paintings portrayed Death as a horridly grinning skeleton that seized, without warning, the prince and the peasant, the young and the old, the lovely maiden and the hardened villain, the innocent babe and the decrepit dotard.

Along with the mood of despair there was a marked tendency toward wild defiance—loose living and immoralities that were no doubt a desperate kind of reassertion of life in the presence of death. Yet the dominant feature of the time was not its licentiousness but its overpowering feelings of guilt, which arose from the conviction that God had visited the plague on man as retribution for his sins. Boccaccio, a few years after writing his *Decameron*, was overcome by repentance and a sense of guilt verging on panic. Martin Luther suffered acutely from guilt and fear of death, and Calvin, terror-stricken by the plague, fled from each epidemic. Indeed, entire communities were afflicted with what Freud called the primordial sense of guilt, and they engaged in penitential processions, pilgrimages and passionate mass preaching.

Some 70 years ago the English Catholic prelate and historian (later cardinal) Francis Gasquet, in a study entitled *The Great Pestilence*, tried to demonstrate that the Black Death set the stage for the Protestant Reformation by killing off the clergy and upsetting the entire religious life of Europe. This no doubt is too simple a theory. On the other hand, it is hard to deny that the catastrophic epidemics at the close of the Middle Ages must have been a powerful force for religious revolution. The failure of the Church and of prayer to ward off the pandemic, the flight of priests who deserted their parishes in the face of danger and the shortage of religious leaders after the Great Dying left the people eager for new kinds of leadership. And it is worth noting that most if not all of the Reformation leaders—Wycliffe, Zwingli, Luther, Calvin and others—were men who sought a more intimate relation of man to God because they were deeply affected by mankind's unprecedented ordeal by disease.

This is not to say that the epidemics of the late Middle Ages suffice to explain the Reformation but simply that the profound disturbance of men's minds by the universal, chronic grief and by the immediacy of death brought fundamental and long-lasting changes in religious outlook. In the moral and religious life of Europe, as well as in the economic sphere, the forces that make for change were undoubtedly strengthened and given added impetus by the Black Death.

MATHEMATICAL GAMES

The hypnotic fascination of sliding-block puzzles

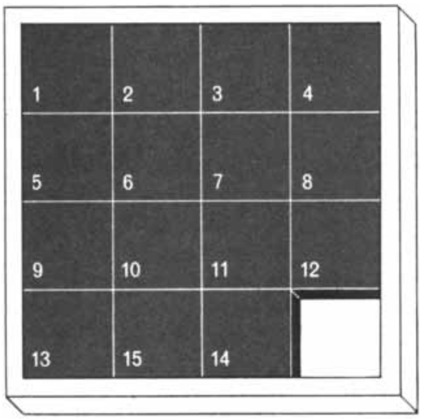
by Martin Gardner

"The older inhabitants of Puzzleland," wrote Sam Loyd in his *Cyclopedia of Puzzles,* "will remember how in the early seventies I drove the entire world crazy over a little box of movable blocks which became known as the 14–15 Puzzle." Fifteen numbered blocks were placed in a square box as shown in the upper illustration on this page. The object was to slide the blocks about, one at a time, until the 14–15 error was corrected and all blocks were in serial order with the empty space in the lower right-hand corner as before.

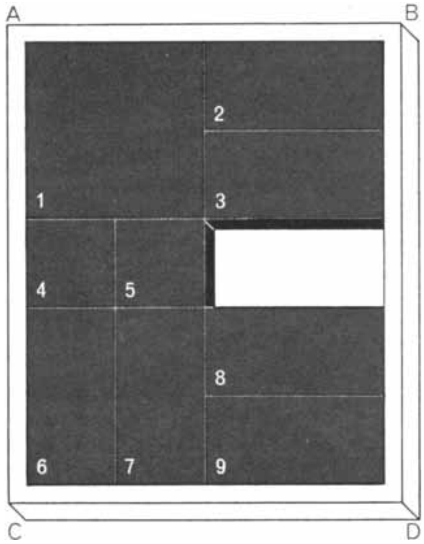
The craze spread rapidly to Britain and Europe. "People became infatuated with the puzzle," Loyd continued, "and ludicrous tales are told of shopkeepers who neglected to open their stores; of a distinguished clergyman who stood under a street lamp all through a wintry night trying to recall the way he had performed the feat.... A famous Baltimore editor tells how he went for his noon lunch and was discovered by his frantic staff long past midnight pushing little pieces of pie around on a plate!"

Interest in the puzzle abated after several mathematicians published articles proving it could not be done. Today the puzzle (still on sale in a variety of forms) is sometimes cited by computer experts as a miniature model of what is now called a sequential machine. Each movement of a block is an input, each arrangement, or "state," of the blocks is an output. It turns out that exactly half of the 15! ($1 \times 2 \times 3 \ldots \times 15$), or 1,307,674,368,000, possible states of the machine are achievable outputs. The mathematical theory of the 14–15 Puzzle applies to all sliding-block puzzles in which the pieces are unit squares confined to rectangular fields.

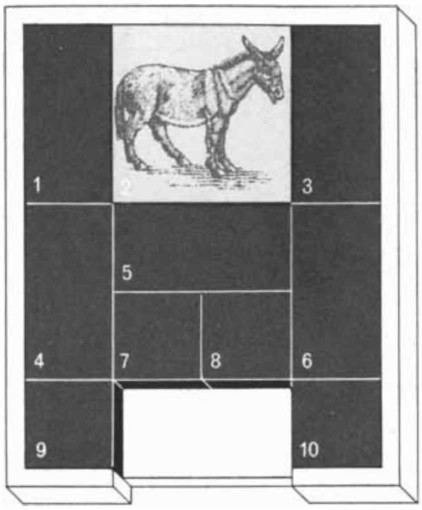
But not to sliding-block puzzles in which the pieces are *not* unit squares! The success of Loyd's puzzle brought a rash of sliding-block puzzles, with differently shaped pieces, that have sold all over the world for the past 80 years. These puzzles are very much in want of a theory. Short of trial and error, no one knows how to determine if a given state is obtainable from another given state, and if it is obtainable, no one knows how to find the minimum chain of moves for achieving the desired state. These entertaining puzzles provide all sorts of challenges for computer programmers. For the rest of us they are engrossing solitaire



Sam Loyd's 14–15 Puzzle



Dad's Puzzle



L'Âne Rouge puzzle

games that can be constructed in a few minutes with only a pair of scissors and a supply of cardboard.

A puzzle of this type—perhaps the earliest and certainly the most widely sold—is shown in the lower illustration on page 122. The reader is urged to stop reading and cut the nine pieces from a sheet of thin cardboard. The diagram is easily copied by drawing a four-by-five rectangle, ruling it lightly into unit squares, then outlining the nine pieces. Number them as indicated, cut them out and place them on a four-by-five rectangle drawn on a sheet of paper or cardboard of contrasting color. The problem: By sliding the pieces one at a time, keeping them flat on the paper and inside the rectangle, bring the large square from corner *A* to corner *C*.

It is easy to bring the square to corner *B*. Move the pieces in order as follows: 5, 4, 1, 2, 3; 4 (up and right), 1, 6, 7, 8; 9, 5, 4, 1, 6; 7, 8, 9, 4 (left and down), 8; 7, 6, 2, 3, 1. This is a minimum-move solution in 25 steps. (Sliding a piece "around a corner" is counted as one move.) To bring the large square to corner *D* requires 29 moves. The first 19 are the same as before, then continue with: 1, 3, 2, 6, 7; 8, 9, 4, 5, 1.

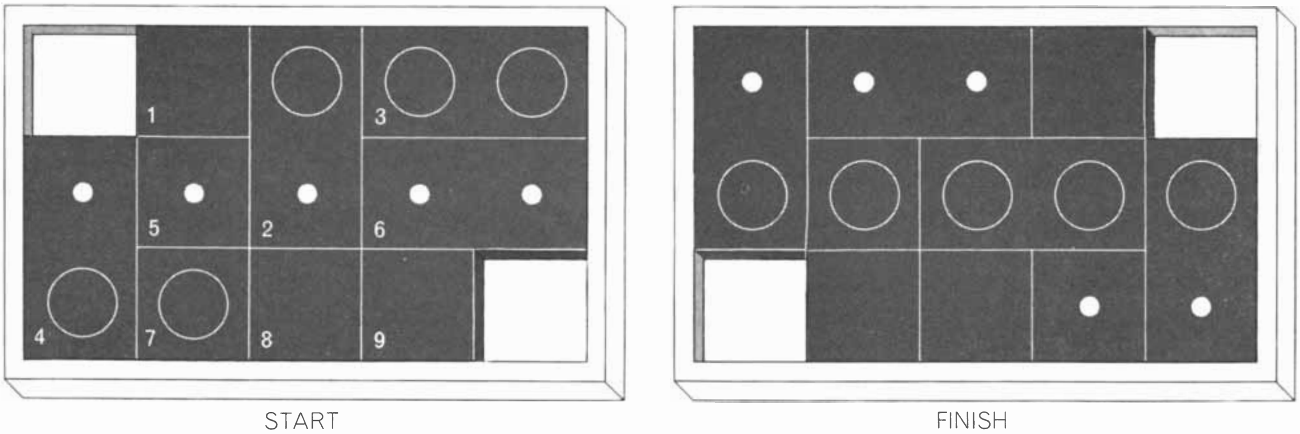
It apparently is not possible to slide the large square from corner *A* to corner *C* in fewer than 59 moves. Readers are urged to see if they can achieve this minimum before the moves are disclosed next month. Cardboard pieces are quite satisfactory, although handsomer and more permanent models can be cut from sheets of wood, plastic, linoleum, Vinylite and so on. The restraining border can be made by gluing strips on a wooden board. The board should be sandpapered for smooth sliding, and it is best to round off the corners of the pieces and bevel their edges slightly.

The origin of this excellent puzzle is unknown. The earliest version in the puzzle collection of the late Lester Grimes of New Rochelle, N.Y., is called the Pennant Puzzle and was copyrighted in 1909 by L. W. Hardy and made by the O.K. Novelty Company in Chicago. Cardboard pieces bear the names of major cities. The large square, which represents the home team, is to be brought to the corner, which symbolizes first place in the league. In 1926 a wooden version was marketed under the name of Dad's Puzzler, and most later versions have been called Dad's Puzzle. An inexpensive version currently on sale has the trade name Moving Day Puzzle (a picture of a piano is on the large square), and there is an elegant version called Magnetic Square Puzzle with large wooden pieces (containing magnets) that cling to a metal field.

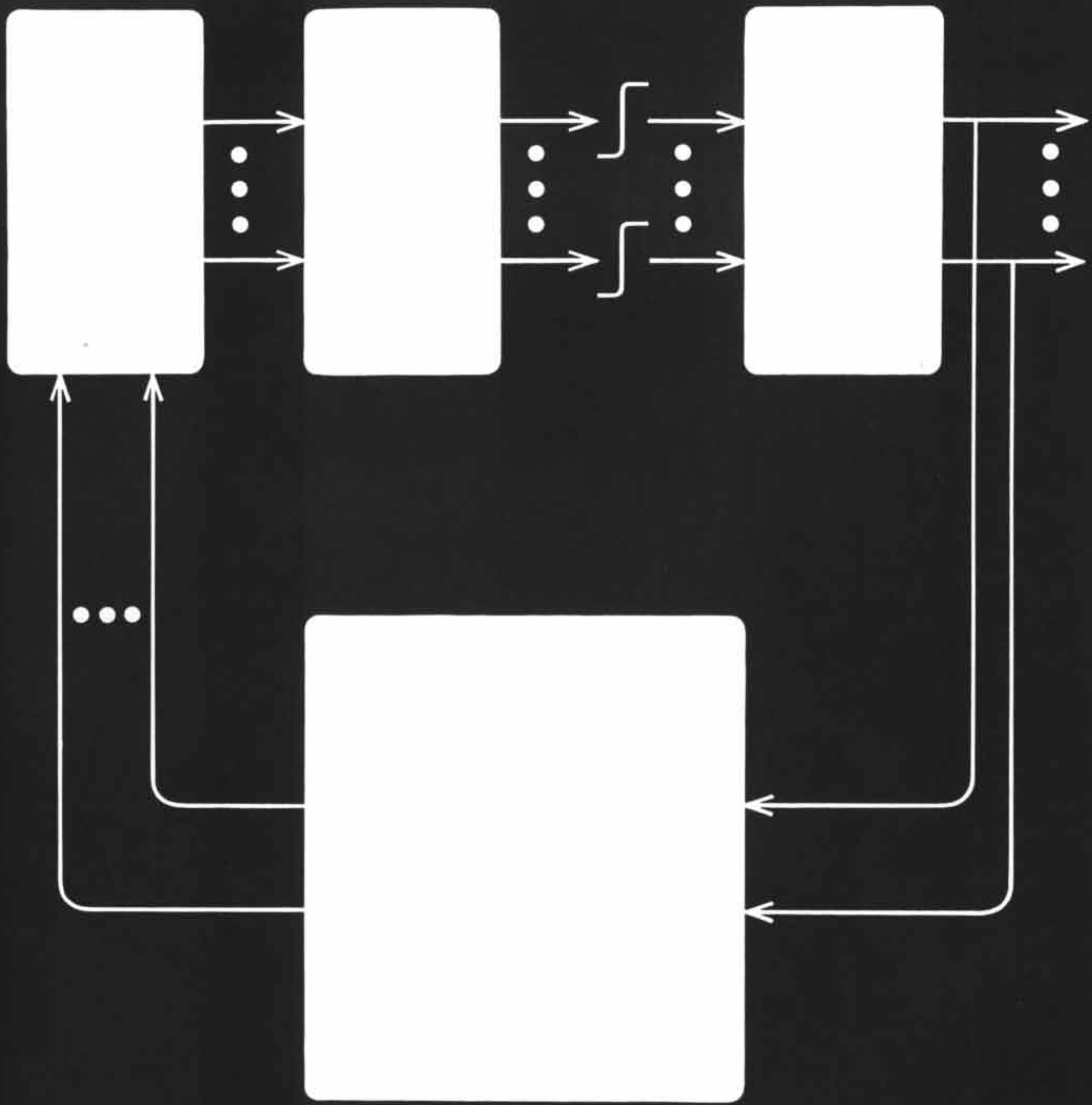
If one of the two-by-one rectangles in Dad's Puzzle is cut in half to make two unit squares, the resulting 10 pieces provide the sliding blocks for a more difficult puzzle [*see illustration at left*] that has long been popular in France under the name of L'Âne Rouge (The Red Donkey). The object of the puzzle is to move the large square with the red donkey's picture to the bottom of the border so that it can be slid out of the box through the opening. A correspondent in Scotland recalls seeing an English version on sale in the early 1930's. More recently it has been sold in this country under such trade names as Intrique, Mov-it Puzzle and Hako. The minimum-move solution is not known, but next month I shall give an 81-move solution worked out by Thomas B. Lemann, a New Orleans attorney.

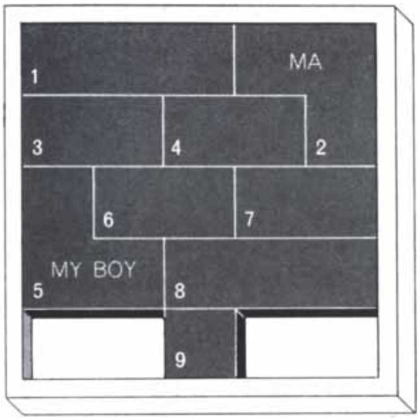
In 1934, when the Dionne quintuplets were born, the event was celebrated by the appearance of an unusual sliding-block puzzle called Line Up the Quinties. (The box bears the imprint of the Embossing Company of Albany, N.Y., and states that the puzzle was created by Richard W. Fatiguant.) In the schematic drawings of this puzzle [*below*] the five circles are the faces of the five quintuplets. The problem is to start with the pieces arranged as shown in the first drawing and move them to the pattern shown at the right. A 30-move solution, the best I have found, will be given next month.

It was inevitable that someone would think of complicating this sort of puzzle by introducing nonrectangular pieces. In 1927 Charles L. A. Diamond of Newburgh, N.Y., obtained patent No. 1,633,-397 for the puzzle shown at the top of page 126. It was manufactured under the name of Ma's Puzzle (in obvious competition with Dad's) by the Standard Trailer Company of Cambridge Springs, Pa. Piece No. 2 was labeled "Ma," No. 5 "My Boy." (The other seven pieces bore the labels "No Work," "Danger," "Broke," "Worry," "Trouble," "Home-



Line Up the Quinties puzzle





Ma's Puzzle

sick" and "Ill.") The object of the puzzle is to unite Ma with My Boy to form a single three-by-two rectangle in the upper right-hand corner of the box. (This rectangle may be either wider than high or vice versa.) I shall give a 32-move solution next month. More complicated puzzles, some all rectangular, others with L-shaped pieces, have been marketed here and abroad.

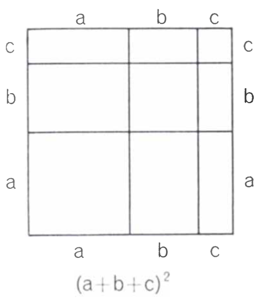
The latest innovation in this curious and unchronicled field has been supplied by Sherley Ellis Stotts, a piano tuner who lives in Denver. Stotts, who holds a master's degree in psychology from the University of Colorado (his thesis was on the reliability of the Seashore music tests), has been blind since the age of seven. In recent years he has invented and made a variety of unusual puzzles out of wire, wood and plastic. A patent application is now pending for what he calls his Tiger series of sliding-block puzzles.

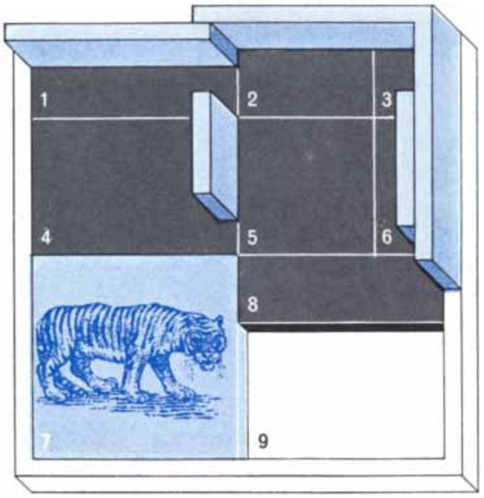
Each tiger puzzle is based on a diagram often used by algebra teachers as a visual display of the square of a polynomial. I shall describe only the simplest Tiger puzzle, which exploits the diagram [*at left in illustration below*] for the square of $a + b + c$. The three terms are represented by the horizontal and vertical line segments on the sides of the square. When the expression is multiplied by itself, the result is $a^2 + b^2 + c^2 + 2ab + 2ac + 2bc$. Each term, of course, is represented in the figure: there are three squares with sides, respectively, of a, b and c, two rectangles with sides ab, two with sides ac and two with sides bc. Stotts converted this dissection to the charming puzzle shown at the right in the illustration. On the large square he glued a replica of a tiger. At the upper right-hand corner he attached to the frame two segments of a fence (shown in color). Three other fence segments were glued to pieces 1, 4 and 6 as shown. (Readers who wish to try the puzzle may simply draw the fences on cardboard pieces.)

The puzzle starts with the pieces arranged as indicated, except that piece 9 is removed from the field. The problem is to slide the pieces so that the tiger square is moved to the upper right-hand corner and completely surrounded by a square fence. Unlike all previous sliding-block puzzles, the open space is large enough to allow, at times, the 90-degree *rotation* of a rectangular piece. This is permitted, of course, only when the rotation is geometrically possible within the space, keeping all pieces flat on the field. Next month I shall give Stotts's 49-move solution. His larger Tiger puzzles are much more difficult; in fact, they are the most difficult sliding-block puzzles I know.

At the moment there is no practical application for a theory of sliding-block puzzles with differently shaped pieces, but it would be foolhardy to say that none will ever be found. As automation advances, complex problems arise in connection with the efficient storage and retrieval of goods. The day may come when a housewife will dial an order to a department store and machines will find the items and deliver them to a post office or truck. If the items are kept in rectangular packages, it is not inconceivable that a certain amount of package-shifting, within confined areas, will be called for. Something of this sort actually goes on constantly in big-city garages and parking lots where it is necessary to park as many cars as possible within the available space and to retrieve the cars with maximum efficiency. In fact, in Britain sliding-block puzzles are often called "garage puzzles" because several British versions have presented the pieces as cars confined to a garage. The problem, of course, is to maneuver a certain car to the garage's entrance without taking any of the other cars outside.

As the reader will quickly discover if he tries to solve any of these puzzles, there is an almost hypnotic fascination in pushing the pieces about in search of a minimum chain of inputs that will produce the desired state. It is by no means all trial and error. The mind soon "sees" that certain lines of play lead to blind alleys whereas other lines of play are promising. I cannot answer every letter, but I shall welcome all solutions in fewer moves than the numbers here given as minimums.





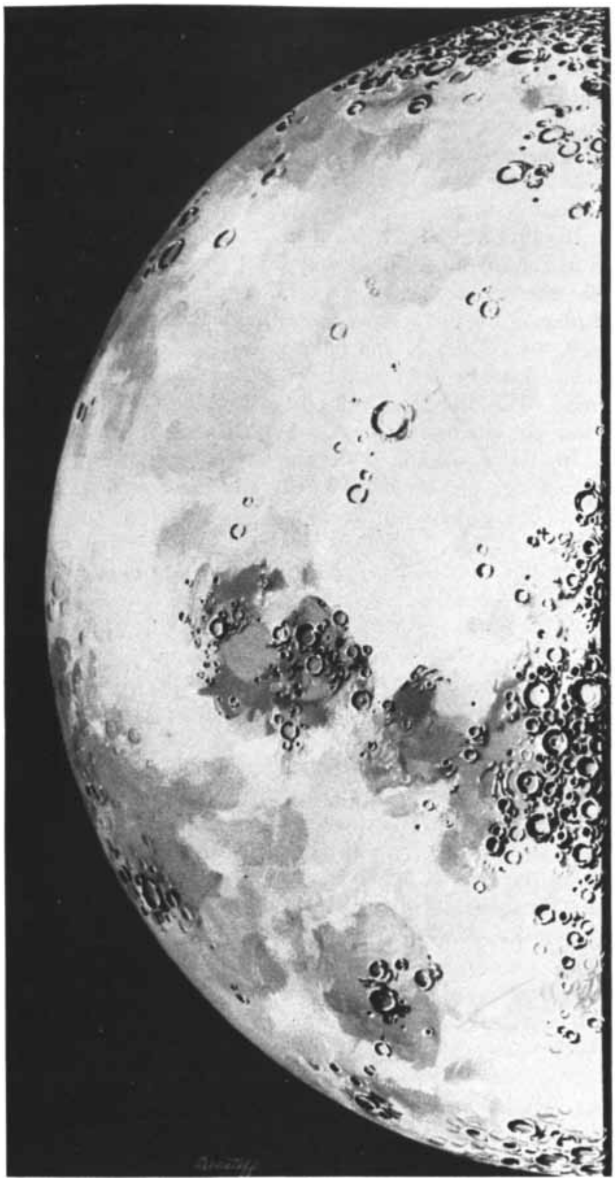
Stotts's Tiger puzzle

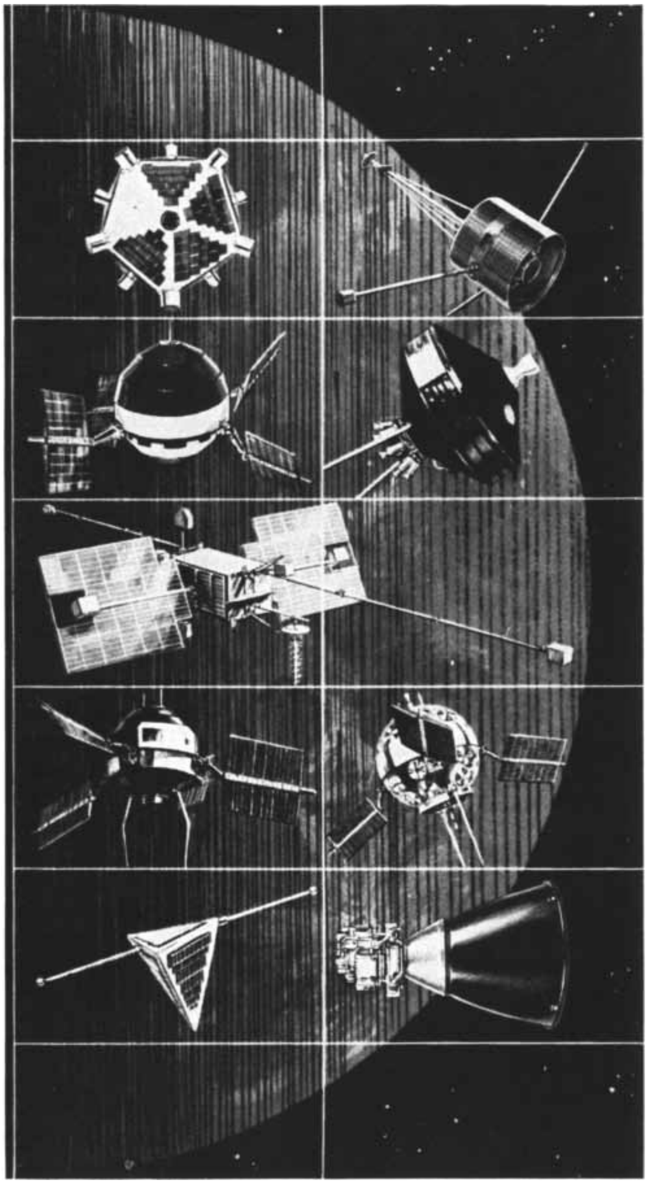
To convert Dr. Matrix' multiplication square to a division square (the first of last month's problems) merely exchange each corner number with the one diagonally opposite. The magic-division constant is 6, the smallest possible number. Curiously, when this same procedure is applied to the familiar order-3 magic square, which sums to 15, the matrix is changed to a subtraction square. If the end digits of any line of three are added and the middle digit is taken from the sum, the result is 5.

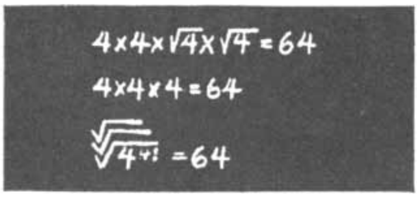
The number 19 can be expressed with four 4's, aided by arithmetical signs and the decimal point only, as follows:

$$\frac{4+4-.4}{.4} = 19$$

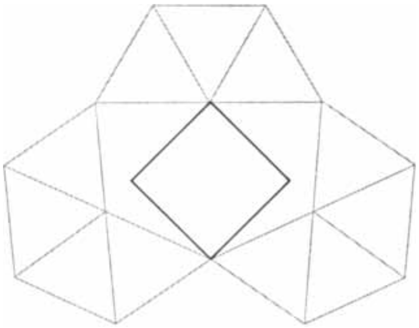
Note that this formula also gives 19 when *any number whatever* is substituted for 4. This is true of many of the other four-4's formulas given last month and suggests an interesting generaliza-



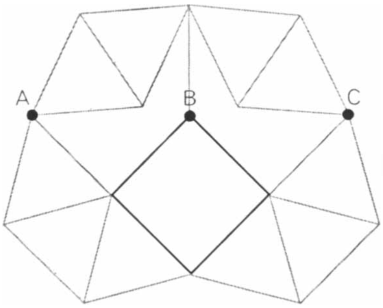




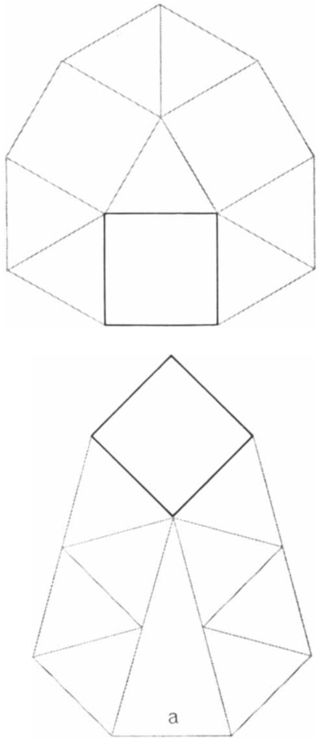
64 expressed with 4's



25-rod solution for square-bracing



23-rod solution



Two incorrect solutions to square-bracing

tion of the pastime: How many positive integers, starting with 1, can be expressed with four *n*'s under the traditional limitations of permissible symbols?

The simplest methods I know for expressing 64 with four 4's, three 4's and two 4's are in the top illustration at the left. For most of last month's numerological nonsense about the Presidential hopefuls I am indebted to Dmitri Borgmann of Oak Park, Ill., the country's leading expert on word play.

Last November's problems brought an unusually heavy mail. The third cryptarithm, which I thought no one could solve without a computer, was solved with pencil and paper by no fewer than 53 readers. The first six solutions received were from William E. Lambert, a chemistry student at the California Institute of Technology; Richard Cherlin, a high school senior in Brooklyn, N.Y.; Marijane Sidote, a housewife in Munster, Ind.; Myron Myerson, New Britain, Conn.; Harry W. Hazard, Princeton, N.J., and Mrs. William L. Avery, Greenlawn, N.Y. Few of the solvers went on to show that no other solution was possible. Six readers, however, programed computers to check all possibilities, and they confirmed the uniqueness of the answer.

The answer (given in December) of 31 extra rods to "rigidify" a square was reduced to 25 rods [*see second illustration from top at left*] by 44 readers. As I was recovering from the shock of this elegant improvement seven readers—G. C. Baker, Joseph H. Engel, Kenneth J. Fawcett, Richard Jenney, Frederick R. Kling, Bernard M. Schwartz and Glenwood Weinert—staggered me with the 23-rod solution shown in the next illustration at the left. The rigidity of the structure becomes apparent when one realizes that points *A*, *B* and *C* must be collinear. All solutions with fewer than 23 rods proved to be either nonrigid or geometrically inexact. For example, many readers sent the pattern shown in the second drawing from the bottom at the left, which is not rigid, or the pattern shown at the bottom, which, although rigid, unfortunately includes line *a*, a trifle longer than one unit.

Readers kind enough to send squared circles must forgive me for not mentioning names; more than 1,000 squares had been received by December 10. I am embarrassed to confess that what I thought was a new problem turns out, as Borgmann informed me, to be one of the first English word squares ever published! In a letter to the British periodical *Notes and Queries* for July 21, 1859, a reader signing himself "W. W." spoke of the word-squaring game "which has of late been current in society" and proceeded to give the following example: Circle, Icarus, Rarest, Create, Lustre, Esteem. "There are very probably," he wrote, "other ways of squaring the circle."

Yes, readers of this column found more than 200 different ways of doing it. I despair of summarizing them. The most popular choice for a second word was Inures, with Iberia, Icarus and Isohel following in that order. The square sent by the most (152) people was: Circle, Inures, Rudest, Crease, Lesser (or Lessor), Esters. Almost as many (140) sent essentially the same square, with Lessee and Esteem as the last two words. "This was done with *ease*," wrote Allan Abrahamse, in punning reference to the fact that a main diagonal of this square consists entirely of *E*'s. Fifty-six readers found Circle, Inures, Rumens, Create, Lenten, Essene.

The most popular square with Iberia as the second word was Circle, Iberia, Recent (or Relent, Repent and so on), Create, Linter, Eaters (or Eatery). The most popular with Icarus second: Circle, Icarus, Rarest, Create, Luster, Esters. With Isohel second: Circle, Isohel, Roband (or Roland), Chaise (or Chasse), Lenses, Eldest. Each of these three squares was sent in by more than 60 readers.

Of some 40 other words chosen for the second spot, Imaret was the favorite. More than 25 readers used it, mostly as follows: Circle, Imaret, Radish, Crissa, Lesson, Ethane. Many squares with unusual words were found by one reader only; the following are representative:

Circle, Imoros, Romist, Crimea, Losest, Estate (Frederick Chait).

Circle, Isolux, Rosace, Claver, Lucent, Exerts (Ross and Otis Schuart).

Circle, Idolom, Rococo, Clonal, Lucayo, Emoloa (Jules Leopold).

Circle, Iterum, Refine, Cringe, Lunger, Emeers (Ralph Hinrichs).

Circle, Isaian, Rained, Cingle, Laelia, Endear (Robert Utter).

Circle, Ironer, Rowena, Cnemis, Lenite, Eraser (Ralph Beaman).

Circle, Inhaul, Rhymed, Camise, Lueses, Eldest (Riley Hampton).

Circle, Irenic, Regime, Cnidus, Limuli, Ecesis (Mrs. Barbara B. Pepelko).

A number of readers tried the more difficult task of squaring the square. All together about 18 different squared squares came in, all with esoteric words such as Square, Quaver, Uakari, Avalon, Rerose, Erinea (Mrs. P. J. Federico). Several readers tried to square the triangle, but without success. Edna La-

The shortest distance between two points is often imagination

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lande squared the ellipse: Ellipse, Lienees, Lecamas, Inagile, Pemican, Sealane, Essenes.

Four readers (Quentin Derkletterer, Solomon Golomb, John McClellan and James Popp) independently hit on this delightful squared cube:

C U B E
U G L Y
B L U E
E Y E S

It could pass for a beatnik poem. (Can anyone, asked Elliott Mendelson, square a beatnik?) Derkletterer took off from this square, along a third co-ordinate, and managed to cube the cube: Cube, Ugly, Blue, Eyes; Ugly, Glue, Lull, Yelp; Blue, Lull, Ulus, Else; Eyes, Yelp, Else, Sped [*see illustration below*]. Patrick O'Neil and Charles Keith cubed the cube this way: Cube, Upon, Bold, Ends; Upon, Pole, Olio, Neon; Bold, Olio, Liar, Dora; Ends, Neon, Dora, Snap. Benjamin F. Melkun and Glenn A. Larson found still another cubed cube, then vanished along a fourth co-ordinate and came back with hypercubes for the words Pet and Eat. They were unable to cube the sphere.

Barry Gault proposed palindromic word squares that read the same backward as forward:

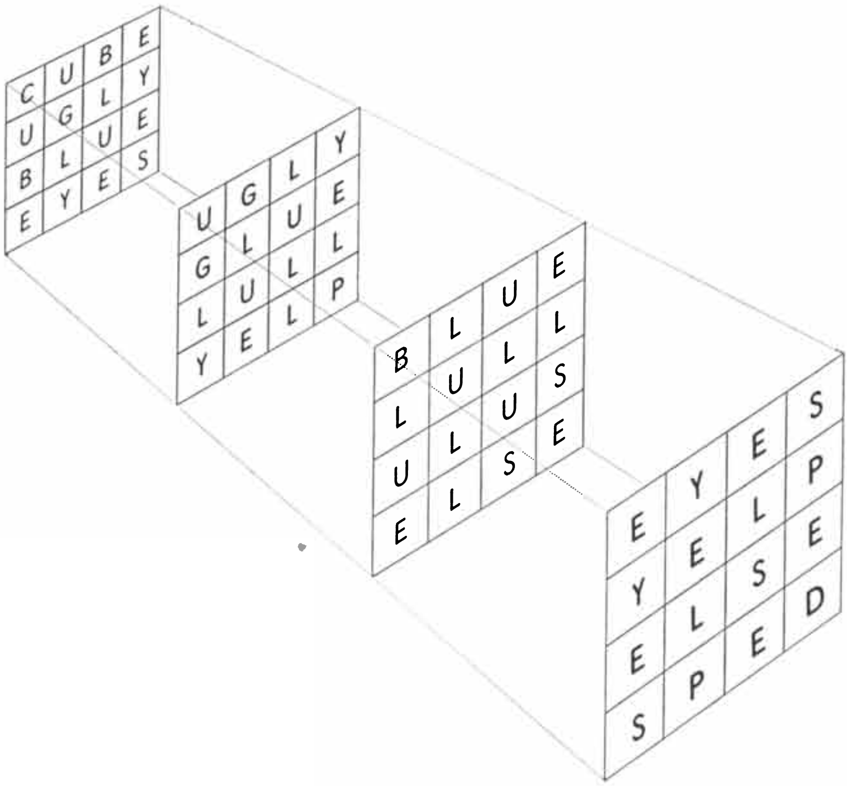
N O
O N

T E N
E V E
N E T

P E T S
E M I T
T I M E
S T E P

Gault was unable to find an order-5 palindromic square. Golomb suggested an even tighter constraint: repeating the same n letters in each word of an order-n square. The order-2 square above qualifies, and the following order-3: Eat, Ate, Tea. No other good examples of order-3 are known, Golomb writes, and no satisfactory order-4 square of this type, which Golomb calls a Latin word square, has yet been discovered.

Among the many readers who solved the chess problem, the following supplied detailed proof that 100 moves is indeed the maximum: Ethan Bolker, Charles M. Bond, George Brewster, Carl E. Diesen, Louise Fernandez, John P. Filley, John R. Geyer, Roger A. Golde, George L. Lupfer, George P. Richardson, J. Schutter, Frank and Morris Sinclair, Crocker Wight and Harry C. Winter.



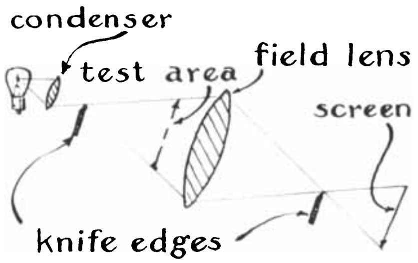
"Cube" cubed

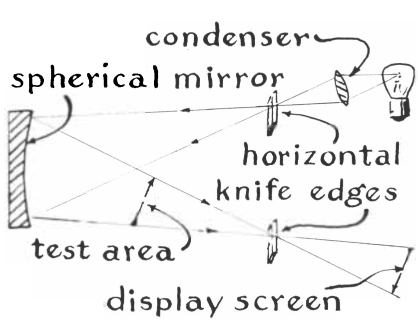
THE AMATEUR SCIENTIST

How to photograph air currents in color and build an accurate Foucault pendulum

Conducted by C. L. Stong

Stars twinkle, mirages appear in desert country and paved highways shimmer under the summer sun because air that rises above warm objects is less dense than the surrounding air. Such differences in density alter the refractive property of air and thereby bend light rays from their normal paths. The effect can be used to photograph normally invisible phenomena such as convection currents in air as well as the flow of air around speeding objects, including bullets and the wings of model airplanes. Recently Robert Walan, then a senior at the Carnegie Institute of Technology, built an apparatus for photographing air-density variations that not only records convection currents and flow patterns but also represents zones of different pressure within the patterns in different colors.





Two Schlieren systems

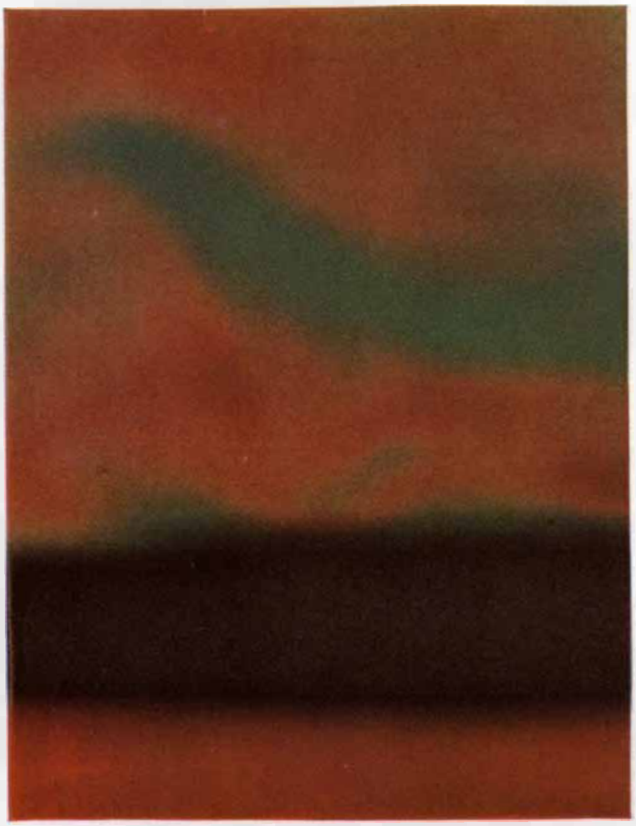
"I built the apparatus in order to analyze the flow of air inside a miniature wind tunnel," Walan writes. "It is essentially a system for making what are called Schlieren photographs, but it differs from conventional Schlieren systems in that it records refraction effects in selected colors rather than in monochrome.

"In the conventional Schlieren system light from a small source is focused on a knife edge adjusted in such a way that the edge intercepts part of the rays. The unobstructed rays that proceed beyond the knife edge are focused by a second lens (or a parabolic mirror) to graze in turn a second knife edge parallel to the first. An opaque object placed in the cone of light between the first knife edge and the second lens, a region known as the test section, will appear in silhouette at the image plane of the lens beyond the second knife edge, where it can be projected on a viewing screen or a photographic film [*see illustration at left below*].

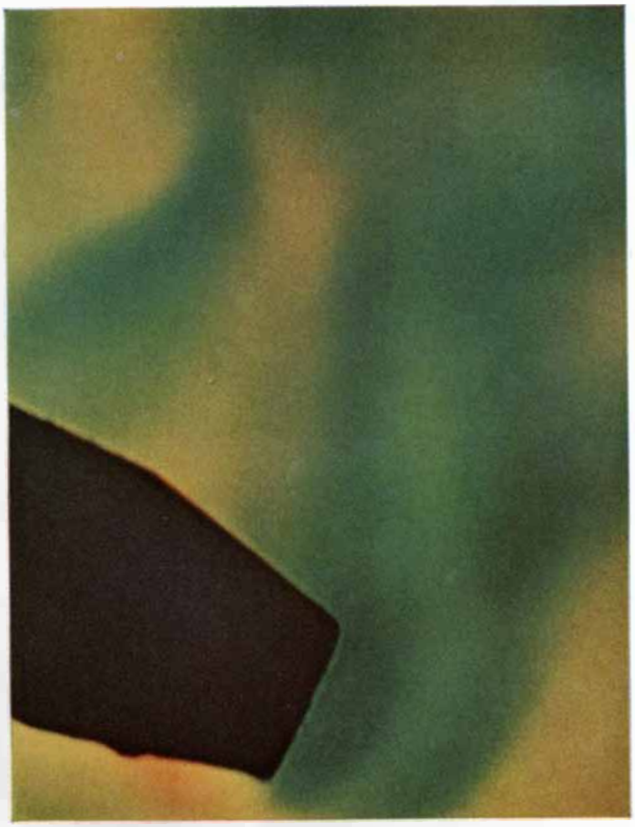
"When the air in the test section is uniformly dense, all parts of the screen are lighted equally except the portion shadowed by the object; the intensity of the light that reaches the screen is determined by the amount of light intercepted by the knife edges. When a pressure gradient exists in the air of the test area, however, some of the light rays are bent. Some rays that would normally fall on the screen will be intercepted by the second knife edge; the screen will appear darker than normal in the region where these rays formerly impinged. Conversely, some rays that would normally be intercepted by the knife edge will be refracted away from the edge and will now reach the screen, adding to the background illumination and making the screen in certain areas brighter than average. As a result of both effects, variations of density in the test area appear on the screen as patterns of light and shade. If the temperature of the object in the test section differs from that of the surrounding air, convection currents form and their image can be seen rising from the silhouette.

"The system is attractive as an analytical device because its action depends solely on light. It has no moving parts and therefore is free of inertia effects, and there is no mechanical linkage to the test object that might affect the free movement of air. The results are easy to interpret and can be expressed quantitatively by measuring the images with an inexpensive light meter. One problem, however, is that the system is extremely sensitive to the quality of the optical parts, since defects in the lenses or parabolic mirrors can also bend light rays. (Indeed, a similar apparatus, the Foucault knife edge, is used routinely by optical workers to check the quality of both lenses and mirrors.) Hence the apparatus must be equipped with lenses that are carefully corrected, particularly with respect to spherical and chromatic aberration. Small lenses of the required quality are comparatively inexpensive. The diameter of the test section is determined, however, by the diameter of the second lens; most experiments require a test section at least three inches in diameter. The cost of corrected lenses of this diameter was beyond me, so I substituted parabolic mirrors, which can be made inexpensively by the methods suggested in *Amateur Telescope Making: Book One*, edited by Albert G. Ingalls (Scientific American, Inc., 1962).

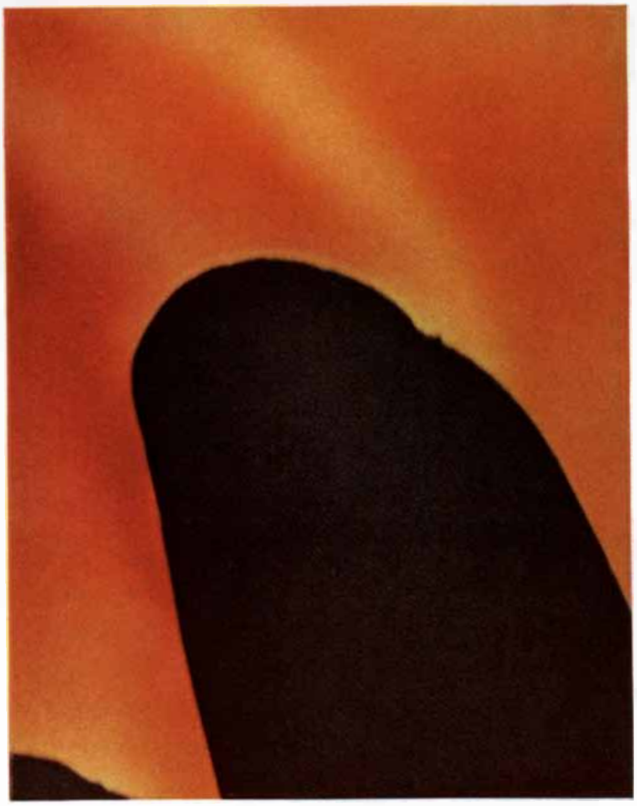
"When a single parabolic mirror is substituted for the second lens in a simple Schlieren system, the arrangement introduces a particularly undesirable form of distortion known as coma. Light from the source must fall on the mirror at rather a large angle in relation to the optical axis or the image will be reflected to a position so close to the source that it cannot be examined. Coma, which increases in proportion to the angle of reflection, makes a point source appear as a small comet shape. Fortunately Schlieren systems can be constructed in a variety of ways. In one popular arrangement light from the source falls on



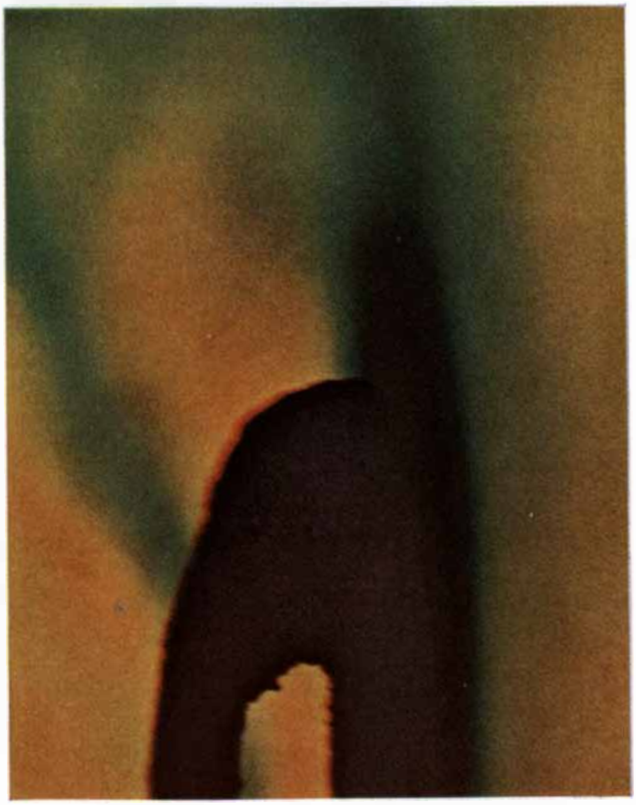
Evaporation from hot plate (compressions, red, expansions green)



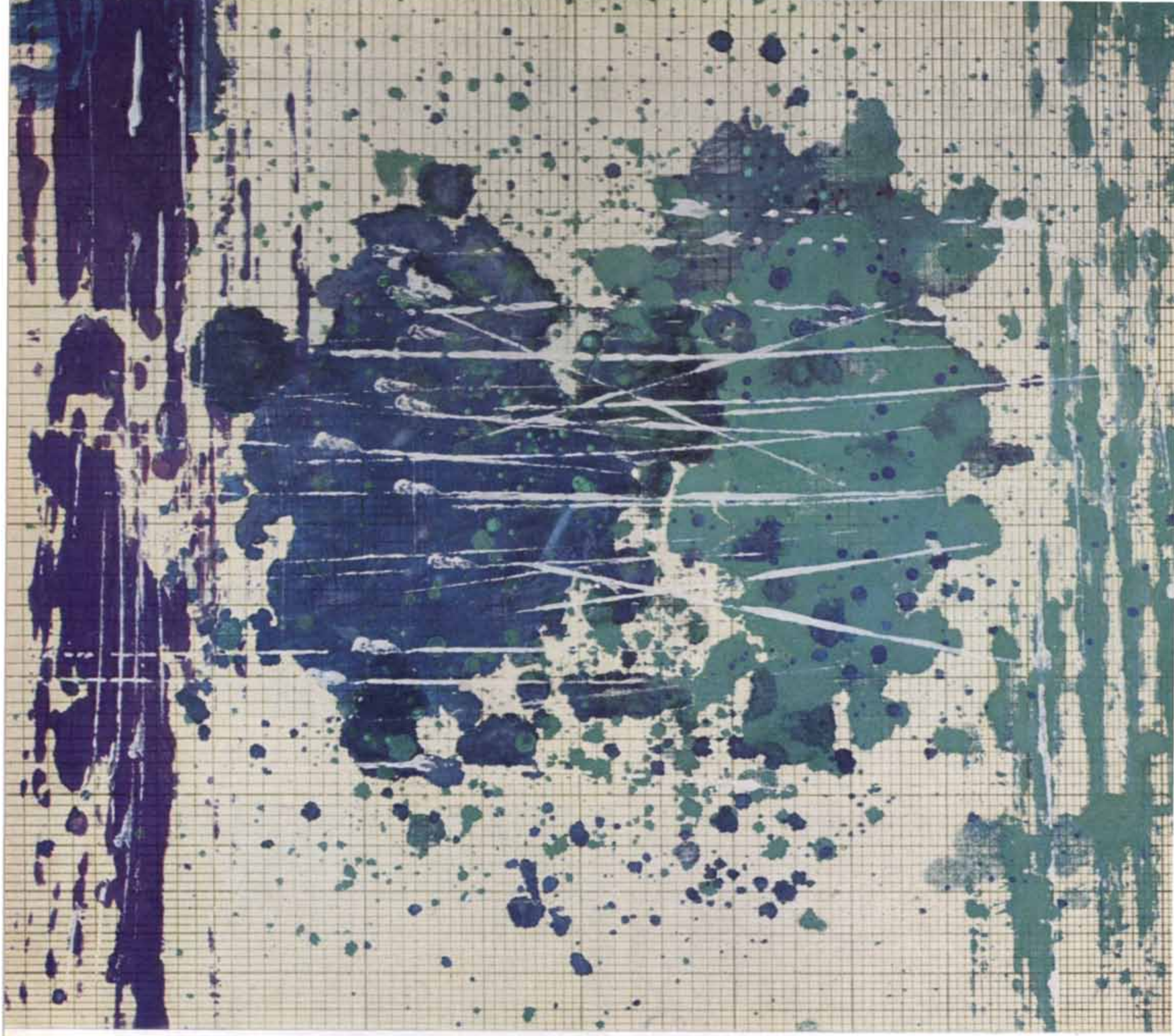
Steady-state convection from heated soldering iron



Convection current rising from human finger



Boundary layer on quick-heating soldering iron



a parabolic mirror from one side and is reflected to a second parabolic mirror from which the rays proceed to a screen on the opposite side. Coma is canceled in the course of the double reflection from opposite sides. The light between the two mirrors is transmitted as parallel rays: a collimated beam that produces maximum detail in the image. The test section lies between the mirrors, and its length, which depends on the separation of the mirrors, can be made as long as one wishes. By adding two small condensing lenses and a direct-vision prism and substituting a pair of adjustable slits for the knife edges, I converted the arrangement into a color system, as illustrated by the accompanying schematic diagram [*top illustration on this page*].

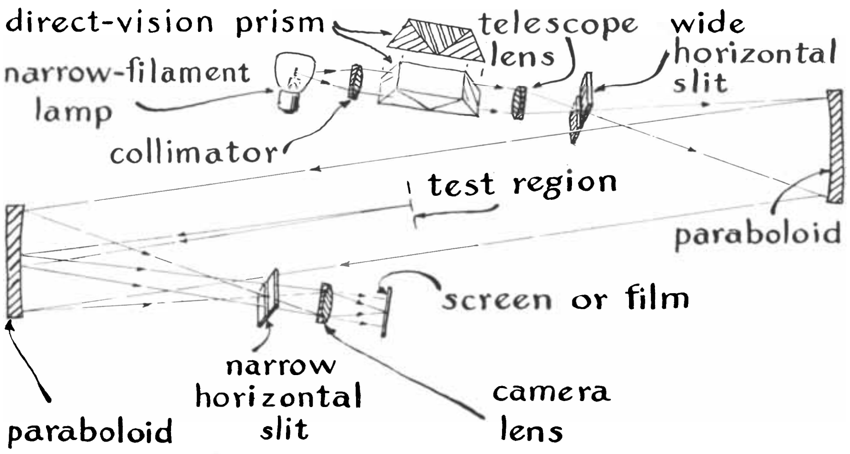


Diagram of color Schlieren system

"A line source of white light (such as the straight, narrow filament of an automobile spotlight bulb) is placed at the exact focus of a small achromatic condensing lens. The collimated rays that emerge from the lens traverse the prism and are dispersed into their spectral colors. Then they are focused by a second condensing lens onto a slit adjusted to transmit a sharply defined beam of colored light. A parabolic mirror located exactly one focal length from the slit receives the converging rays and reflects them as a collimated beam to a second parabolic mirror, which in turn focuses the image of the source on a second slit assembly located on the opposite side of the apparatus, as illustrated. The second slit is adjusted to intercept all but one color of the beam. An objective lens beyond the second slit functions as a camera and projects an image of the test section on a screen or color film.

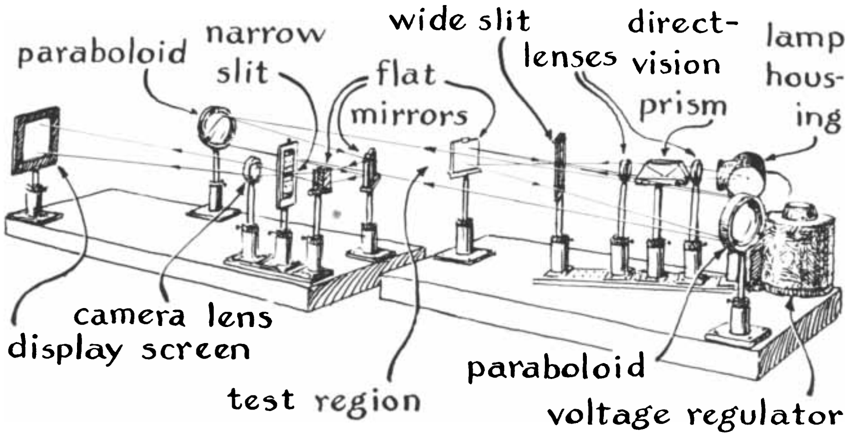
"When the density of the air in the test section (the region between the two parabolic mirrors) is uniform, the screen is uniformly illuminated and is monochromatic. When variations of density in local regions of the test section refract the rays, other colors, which would normally be intercepted by the edges of the slits, are transmitted to the screen, replacing the background color. The image then appears in polychrome, with higher densities depicted by a color nearer one end of the spectrum and low densities by a color on the opposite side.

"I usually adjust the second slit to pass the orange-yellow part of the spectrum. This creates a yellowish background when the air of the test section is of uniform density. The first slit is then adjusted to pass the red-orange-yellow-green segment of the spectrum. Compressions appear in red and expansions in green, as illustrated by the accompanying color photographs [*page 133*]. The sensitivity of the system, which depends on the position and focal length of the mirrors and the width of the slits, is broad enough to accommodate disturbances set up in the test chamber by objects as different in temperature as a hot soldering iron and a finger.

"The optical system of a color Schlieren apparatus is not difficult to design. The experimenter arbitrarily selects the desired diameter of the test section. I decided on a width of three inches. This determines the diameter of the parabolic mirrors. To minimize the effects of optical aberrations such as coma and astigmatism (the tendency of mirrors to focus lines in one orientation more sharply than in others) a focal length must be selected that allows the entrance and exit cones of rays to make an angle of not more than five degrees in relation to the parallel rays of the test section. The focal length of my mirrors was 11 times the diameter of the mirrors, a focal ratio, or 'speed,' of $f/11$. A higher focal ratio may be selected, but a lower one invites construction difficulties. (At $f/11$, incidentally, the curvature of a 'parabolic' mirror is essentially a section of a sphere, a fairly easy surface for amateurs to grind and polish.)

"The geometry of the mirrors determines the minimum over-all length of the system, which is twice the focal length of the mirrors. The lens and slit components can be located at any desired angle with respect to the test section by deflecting the entrance and exit cones to the side by means of plane, front-surfaced mirrors. (The insertion of each additional surface in the optical path causes approximately a 5 per cent loss of light.) When a camera lens is not present, the second mirror forms a real image in its focal plane. When a camera lens is added, the proper location of the screen and film plane is determined experimentally.

"For maximum performance the system must be carefully aligned so that all components of the optical train, including the slits, are symmetrical in relation to the optical axis. The components must



Structural assembly of color Schlieren system be rigidly mounted on vibrationless supports. I machined the mounting fixtures from brass and slotted the bases of most fittings for hold-down screws so that they can be shifted about half an inch in either direction along the optical axis. They can also be adjusted vertically. All components can be rotated vertically and moved transversely with respect to the light beam.

"The system is assembled in two units, one comprising the light source, direct-vision prism and associated condensing lenses, the first slit, a deflecting plane mirror and one parabolic mirror. The second unit includes the remaining parabolic mirror, a pair of deflecting mirrors, the second slit, the camera lens and screen. The test section is lengthened by simply sliding the units apart. The base supports of some units are mounted in brass guide plates that confine their transverse movement to one plane, a feature that simplifies the adjustment of the system. After aligning the system initially I made a full-scale drawing of the position of each component directly on the mounting board. The drawing saved a lot of time during subsequent experiments because components could be moved and quickly returned to approximately their proper positions. Final adjustments had to be made, of course, by trial and error.

"Ideally the source of light should be bright, white and in the form of a straight line to match the geometry of the slits. My source is an automobile spotlight bulb designed for operation at 12 volts. When exposing Kodacolor film, I operate the lamp on alternating current at twice its rated voltage. Power is supplied by a 110-volt line through a variable transformer. I made my slits of single-edge safety-razor blades, spraying the sides with white lacquer to improve their visibility.

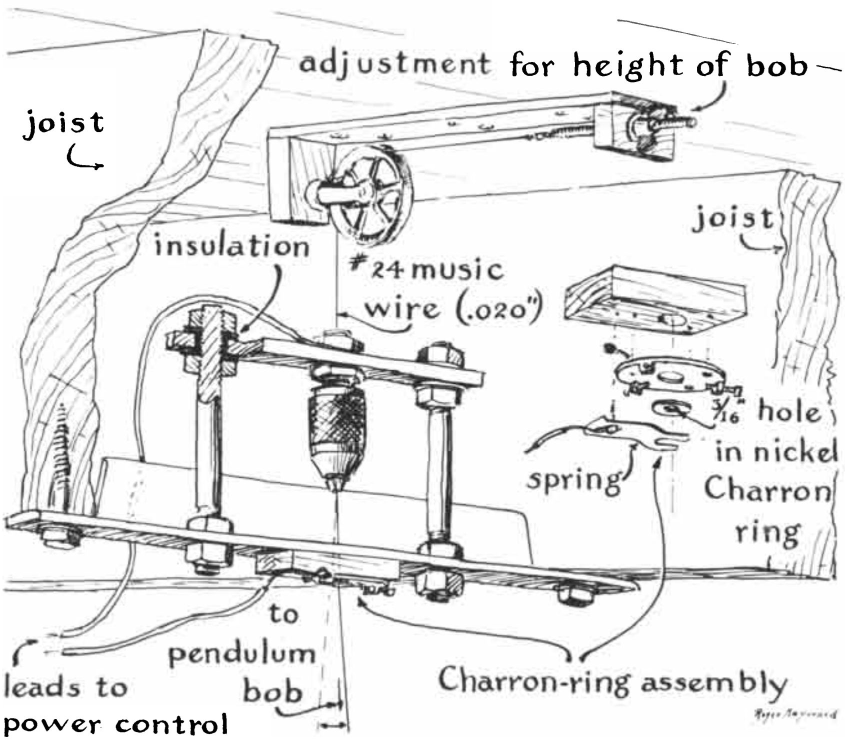
"Although most of my experiments have been made in color, the apparatus can be converted for use as a conventional black-and-white system merely by removing the prism assembly. A direct-vision type of prism is preferred because of its optical properties, but any weak prism in crown glass may be substituted if some loss in performance can be tolerated. Such prisms are inexpensive and can be procured, along with condensing lenses and glass blanks for the parabolic mirrors, from the Edmund Scientific Co. in Barrington, N.J."

The Foucault pendulum is a fascinating demonstration of the fact that the earth rotates in relation to the stars, but it is not a very good timekeeper. In principle the device is merely a weight suspended by a long wire and free to swing in a vertical plane at any orientation. If such a pendulum were to be set swinging directly over one of the earth's poles, the plane of the swing would appear to make a complete rotation in 24 hours with respect to the earth's surface. Since no force acts on the pendulum to alter the direction of its swing, the apparent rotation of the plane of vibration can be explained only on the assumption that the earth rotates. Moreover, when the experiment is repeated at the earth's equator, the plane of vibration remains fixed in relation to the surface. At intermediate latitudes it has been shown that the rate at which the plane of vibration appears to rotate is equal to the time of the earth's rotation (24 hours a day) divided by the trigonometric sine of the latitude at which the experiment is conducted. In the case of short pendulums a correction factor must be applied: the computed rate is multiplied by the factor $(1 - 2A^2/8L^2)$, in which A is the amplitude of the swing and L the length of the pendulum, both quantities expressed in centimeters. At the latitude of New York City (40 degrees 45 minutes North) the ideal Foucault pendulum would appear to complete one revolution in 36 hours 50 minutes.

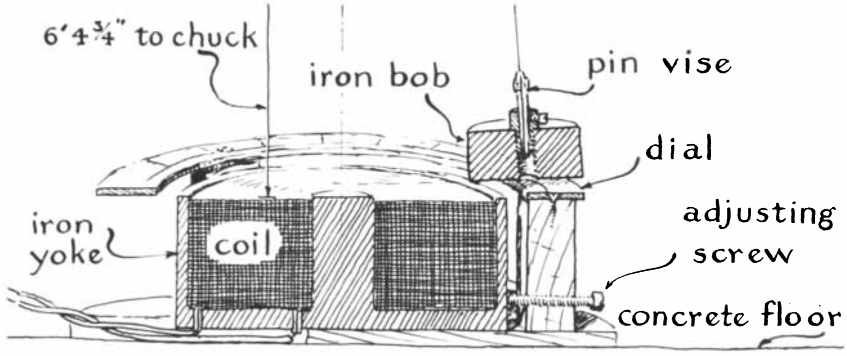
The performance of actual pendulums, however, usually comes only within about 15 per cent of this figure, as mentioned previously in this department [see "The Amateur Scientist," Scientific American, June, 1958]. None of the Foucault pendulums the editor of this department has examined (including the one on display at the Griffith Observatory in Los Angeles and the splendid installation that adorns the entrance hall of the United Nations General Assembly building in New York) betters the 15 per cent error. To B. B. Bingham of Athol, Mass., a deviation from clock time of this magnitude seemed unreasonably large. After some three years of experimentation he has reduced it substantially by constructing a miniaturized version of the Foucault pendulum. Bingham's apparatus keeps time with an average error of only 2 percent on most days and is considerably more accurate on some days.

The design is unusually attractive for home installation because the pendulum is less than seven feet long and is equipped with a transistorized drive. Once started, it runs indefinitely without attention.

The iron bob, cut from a piece of mild steel shafting and fully annealed, is four inches wide and two inches thick. The center is drilled and threaded to take a



Details of Foucault pendulum suspension



Details of electromagnet for driving pendulum

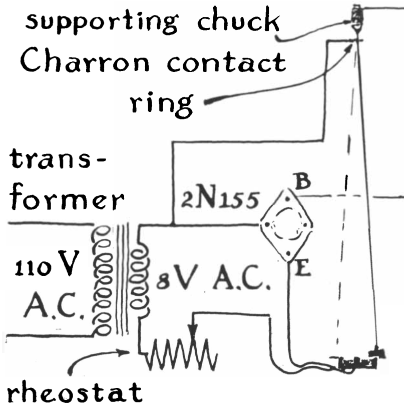
collar that makes a close fit with a pin vise. The pin vise grips the bottom end of a length of No. 24 music wire that serves as the pendulum arm. The upper end of the wire is threaded through a fixed washer, called the Charron-ring assembly, and a three-jawed hollow chuck. It then passes over a suspension pulley attached to the ceiling and fastens to the end of a threaded rod that passes through a fixed bracket and engages a thumb nut, as shown in the illustration on the preceding page. Adjusting the nut alters the length of the wire between the jaws of the chuck and the pin vise and thereby changes the effective length of the pendulum.

The length is initially adjusted so that the bob just grazes a magnet assembly located exactly below the pendulum at the center of its swing. The magnet consists of a concentric yoke, also machined of mild steel and annealed. The yoke has the form of a circular pan 2½ inches deep with an inner diameter of eight inches. A cylindrical pole two inches in diameter extends up from the center of the pan 1/8 inch higher than the edge of the pan [*see illustration above*]. The rectangular toroidal cavity thus formed between the center pole and the edge is fitted with a coil of closely wound, plastic-coated No. 14 copper magnet wire—the maximum number of turns the space will accommodate. The coil is served by a wrapping of plastic insulating tape to make a snug fit with the yoke. Leads from the coil are brought out through two small holes in the bottom of the assembly. The yoke is surrounded by a circular dial divided by hour graduations appropriate to the geographical latitude of the location—36 divisions in the case of Bingham's installation.

The Charron ring, made of nickel, serves both to suppress the pendulum's tendency to vibrate in elliptical or oval paths instead of the desired plane path and to actuate the electric driving circuit. The nickel ring, perhaps appropriately, should have the dimensions of a U.S. five-cent piece, with a 3/16-inch hole exactly in the center. (Do not make the part from a coin; it is illegal to deface U.S. currency.) The Charron ring is clamped, by three adjustment screws spaced 120 degrees apart, to a circular plate three inches in diameter that is in turn fastened to a length of angle iron screwed to ceiling joists. A bracket made of two stud bolts and a second length of strap iron supports the three-jawed chuck.

The height of the chuck must be adjusted so that the tips of the jaws are exactly 2 and 7/16 inches above the lower face of the circular plate that clamps the Charron ring. The various assemblies are then aligned in such a way that the suspension wire hangs exactly in the middle of the chuck, before the jaws are clamped, and exactly in the center of the Charron ring. The center of the magnetic yoke must be placed exactly below the center of the bob when the pendulum is hanging free and motionless.

The electric circuit [*see illustration below*] can be energized by any miniature transformer capable of delivering



Circuit diagram for the drive system

eight volts at 10 watts, or more. One side of the secondary winding of the transformer is connected to the collector terminal of a 2N155 transistor (or its equivalent) and to the Charron ring. The three-jawed chuck connects to the base lead of the transistor and the coil assembly is placed in series with the emitter lead, a 50-ohm rheostat and the remaining lead of the secondary transformer winding. (Alligator clips should be used for making connections to the transistor unless the amateur is familiar with the technique of soldering to these devices. Transistors can be permanently damaged by excessive heat.)

When the installation is complete, adjust the length of the pendulum so that the bob clears the center pole of the yoke by about an eighth of an inch. Clamp the wire in this position by closing the jaws of the chuck. Then start the pendulum with a gentle push, just enough to bring the wire into contact with the Charron ring. This energizes the magnet, which attracts the bob. As the bob approaches the magnet the wire separates from the Charron ring and the magnetic field collapses. The bob now swings free to the opposite side, where the wire again makes contact with the Charron ring, energizing the magnet to initiate the next half of the cycle.

At first the pendulum may follow an elliptical path or a figure eight, but within an hour it will settle into plane vibration. The plane will rotate in a clockwise direction. When the vibration has stabilized, observe its azimuth in relation to the hour circle and also make a note of the time as indicated by a reliable clock. Let the unit operate for 24 hours. If the pendulum runs slow, shorten the wire; if it is fast, lengthen the wire. The amplitude of the swing should be maintained at about 12 to 14 inches, just enough for the wire to make solid contact with the Charron ring. The amplitude can be increased or decreased by adjusting the rheostat in the emitter circuit of the transistor.

Bingham reports that the rate of his pendulum appears to deviate from clock time when the swing is parallel to the earth's magnetic field and to be synchronous with the clock when the swing is at a right angle to the magnetic field. The plane of the swing rotates faster than the clock as it proceeds from west to north and slower in the east-to-south segment. The maximum deviation never exceeds 4.5 per cent of true clock time, however—well under the 15 per cent error that is considered normal for Foucault pendulums.

BOOKS

On the possibility of communicating with intelligent life elsewhere in the universe

by James R. Newman

INTERSTELLAR COMMUNICATION, edited by A. G. W. Cameron. W. A. Benjamin, Inc. ($8.50).

"We are in great haste to construct a magnetic telegraph from Maine to Texas; but Maine and Texas, it may be, have nothing important to communicate." Now, a little more than a century since Thoreau entertained this irony, we are once more confronted with the possibility of enlarging the universe of human jabber—not, thank heaven, between Maine and Texas, but between our small planet and the possible inhabitants of other planets. A contemporary cynic might inquire: "What have we got to tell that is worth sending billions of miles into space?"; but before we can indulge ourselves in the luxury of such skepticism there is much to be found out. Is there life on other planets in our solar system? Are there other stars in our galaxy that have planets? Is it reasonable to assume that, if such planets exist, some are life-bearing? If some are, have their organisms evolved to the stage of man? If so, do these organisms have advanced societies that are capable of communicating with us or of receiving signals we might be capable of sending them? Or are they so far beyond us they would no more waste time in talking to us than we would seek to confer with a midge? To be practical, if someone is out there, how do we engage his attention?

These are the main questions dealt with in this engrossing anthology assembled and edited by a Canadian astrophysicist now working at the Institute for Space Studies in New York. Not too long ago such an anthology would have been pure science fiction. The developments of the past 20 or 30 years, however, have drastically altered the outlook of even hardheaded theoreticians, experimentalists and engineers. The reprints and original articles constituting this book come from astronomers, physicists, mathematicians, biochemists, electrical engineers and practitioners of other specialties, all of them concerned with the possibility of interstellar communication. Some are more imaginative than others, more philosophically disposed, more poetic, more awed, more scared of what might pop out at them. Not all scientists, after all, are speculative or reflective; there are lots of clever fellows who merely want to make the key with which to open the lock. But a high proportion of the contributors to Cameron's collection are aware of the implications for man of this branch of study, and all seem to think there is a pretty good chance we are not alone in the galaxy and that in the foreseeable future evidence may be found to complete this final phase of the Copernican intellectual revolution.

A long chain of reasoning and observation has brought us to the portal of the new adventure. For centuries, perhaps millenniums, men could freely speculate, as did Teng Mu, a scholar of the Sung dynasty, about "other skies and other earths." But knowledge, like the Lord, giveth and taketh away, and so, at the same time as our universe expanded and our windows on it became more ample and numerous, certain theories arose concerning scientific limits and impossibilities. With respect to the possibility of life, not to say intelligent life, in other worlds, a limit was imposed by the respected cosmogonic hypothesis of Sir James Jeans. In his view the solar system was the product of a chance encounter between two stars. In this catastrophe the earth and the other planets were spun off as debris. But such encounters must be rare, because stars are tiny compared with the distances between them. Therefore planetary systems such as ours must be extremely rare.

Jeans's hypothesis, however, came under attack in the 1930's. Several nearly unanswerable points were raised against it. Astrophysicists calculated that fragments drawn out of the sun by a grazing star would fall back into the sun. It was suggested by Henry Norris Russell (and later mathematically demonstrated by the Soviet astronomer N. N. Pariysk) that a collision or near collision could not explain the circumstance that 98 per cent of the angular momentum of the system is contained in the planets and only 2 per cent resides in the sun. The hypothesis was gradually supplanted by the notion that sun and planets condensed simultaneously out of one cloud of gas and dust. It is now believed that this is the usual process of star formation, and the inference has been drawn that many stars are accompanied by planets. This is the first link of the chain.

How many systems physically resembling ours are there? Our galaxy is estimated to have a population of the order of 100 billion stars. Many of these, it is thought, either never had planets or swallowed them as they were being born. The very massive stars formed from the larger gas clouds, for example, rotate much more rapidly than the sun and exert a formidable gravitational attraction. They seem to contain the entire angular momentum of the parent cloud, which is to say they share none of it with planets. This still leaves a vast number of stars as likely candidates. It is a plausible deduction that these stars have, in Philip Morrison's words, "bequeathed their spin to planets." If this reasoning is correct, it is probable that there are at least several billion planets in our galaxy alone.

We have seen none of them. Why? Because the existence of planetary systems comparable to ours cannot, as the Soviet astrophysicist I. S. Shklovsky points out, be detected by astronomical observation, even in the nearest stars. He relates the late Otto Struve's example of an imaginary observer perched in the orbital plane of Jupiter at a distance from the sun of 10 parsecs (a little more than 30 light-years). With the best astronomical instruments now available he would not be able to detect even that giant planet as an object adjacent to the sun. Moreover, when Jupiter passed across the solar disk, as it does once every 11.8 years, it would dim the sun's light no more than a hundredth of 1 per cent, an amount that would be impractical to detect by the best contemporary photometers.

Not every planet would be hospitable to life; an even smaller fraction could support highly organized and intelligent life—as we like to think of ours. Su-Shu Huang has demonstrated that the habitable zone of a planet increases with the luminosity of its sun. There must be enough radiation, otherwise the temperature would be too low to sustain the chemistry of life, and not too much radiation, otherwise the temperature would be too high for such chemistry. In short, the eligible planets must lie in the "Mars-earth region."

We are whittling down the possible number of earthlike planets but we must go further. Our interest, when we envision communication, is in planets that may have intelligent life *now*, not in planets that may once have sheltered it but whose "psychozoic era" has passed, nor in those that may attain this level in the future. Intelligent life on earth has had a span of perhaps a million years. We may be nearing the end, having nibbled too fast on the apple of knowledge and too little on the fruit of the owl. This may be the fate of all advanced societies; dinosaurs lasted longer. Pessimism aside, several time-limiting factors must be taken into account. First, it is highly probable that even under favorable conditions it takes several billion years for the complex beings we are looking for to evolve from the primordial consommé. Second, in the long history of our galaxy it is likely that many stars have played out their role as hosts to life. Third, there is some reason to believe that societies as a whole have a finite span, just as their individual members do.

These considerations point to the conclusion that today only a small fraction of the 100 billion stars of our galaxy have planets that can give rise to life and intelligent beings. The proportion is small, but the congregation of which it is a part is huge; thus a number of the order of 100 million eligible planets may not be wildly wrong.

In our solar neighborhood about 5 per cent of the stars, according to Huang's estimate, may have life associated with them; 41 of these lie within five parsecs (about 16.7 light-years) of the solar system and two, Epsilon Eridani (10.8 light-years) and Tau Ceti (11.8 light-years), have "a good chance" of possessing planets bearing life.

At this point a most important question enters. We have been proceeding on a grand assumption: that given certain simple ingredients and certain sources of energy, life will begin and will evolve in any appropriate cradle. Is this assumption sound? That it probably is, is demonstrated in an admirable article, the longest and best in this collection, by Melvin Calvin.

The essential ingredients are carbon, nitrogen, oxygen and hydrogen. These, together with a few others, are the principal atoms of living material. The primeval atmosphere of the earth, it is conjectured, consisted mainly of four substances: molecular hydrogen, carbon combined with hydrogen as methane, oxygen combined with hydrogen in the form of water and nitrogen combined with hydrogen in the form of ammonia. Out of these everything has to be cooked: organic molecules, trilobites, water lilies, fleas, man.

The beginning of the life process involves tearing atoms from one another, recombining them, tearing them apart and recombining them again and again to form more complex substances. Large quantities of free energy are required for tearing things apart. Among the forms that were available on earth and must be available on other life-bearing planets are ultraviolet radiation (in our case from the sun), cosmic rays, radiation from radioactive elements, and lightning. Calvin and his colleagues performed experiments in 1950 in which a cyclotron was a source of ionizing radiation, to see if they could effect certain basic transformations of simple molecules. The experiments were successful. Starting with carbon dioxide (instead of methane) and hydrogen, the experimenters were able to make reduced, or hydrogenated, carbon compounds such as formic acid and formaldehyde. Since that time the theory of a reducing primeval atmosphere "has become increasingly accepted," and by a wide variety of experiments using ionizing radiation, ultraviolet radiation and electric discharges (lightning) simple molecules have been converted into more complex ones such as acetic acid, succinic acid and the amino acid glycine.

But the achievement itself immediately posed an even more formidable question: Are there more efficient ways to transform these molecules in a manner that will be selective? If these early processes were mere chance affairs, there would be no reason to believe that the complex substances would have endured, let alone have achieved a higher architecture. In the absence of a selective operator the free energy would break up the complexes as quickly as they were being formed, and this random shuttling between construction, destruction and reconstruction would proceed indefinitely and futilely.

It was soon discovered that in the presence of certain substances acting as catalysts the transformations become more selective. The process might run something like this. If substance *A* has a choice of going to substances *B*, *C* or *D*, and if *D* is the kind of substance that for chemical reasons accelerates the rate of the transformation from *A* to *D*, then more of *A* will become *D* than will become *C* or *B*. This is called autocatalysis. *D* makes itself and selects the transformations leading to its own creation.

The next stage requires the passage from complex but still small molecules to the giants: the polymers. The amino acids "constitute one of the principal classes of compounds in which giant molecules can be made by hooking small ones together, end to end. There is an amino (basic) end and an acid end, and these can combine indefinitely to make a long chain which is called polypeptide and which constitutes one of the principal structural materials (protein) of all living things." The biochemist Sidney W. Fox has shown that under what he calls prebiological conditions some of the amino acids could be converted into protein-like substances. By heating up a mixture of some 20 amino acids in molten glutamic acid a little above the boiling point of water he got the amino acids to hook together and make polypeptides.

Calvin describes further researches that have thrown light on the primordial formation of nucleic acids. The twin backbones of these giant molecules are joined by hydrogen bonds between their constituent bases; on the outside of the bases rows of sugar molecules linked by phosphate groups act "as though two ribbons were tying together the edges of a row of playing cards." If these ribbons are twisted, the playing cards will instead of lying flat turn sideways and stack up. Flat molecules do stack up under certain conditions: they crystallize. Although the stacking up is spontaneous, the order that the four kinds of base (thymine, adenine, cytosine and guanine) can follow "apparently contains the necessary information . . . which tells the present-day organism what to become. This arrangement of bases contains the genetic information of a modern organism."

The path from chaos to order is exquisitely intricate, but we have vital clues to it. The staircase to the giant molecule is understood, but as yet the organization of these giant molecules into larger structures can only be conjectured. Again, Calvin suggests, crystallization is the means of ascent. Even so, even though certain macroscopic structures can under the proper conditions be precipitated out of solutions of giant molecules, the structures are far different from living cells. They lack, among other things, the membrane that separates the cell from its environment. There are, however, physicochemical mechanisms for producing enclosing membranes. For example, if a film of oil is lying on a layer of protein that in turn is resting on water, the film rolls up into droplets, some enclosing air, some water. F. Millich and Calvin have shown that, when one takes a fairly dilute solution of a synthetic polymer and adds a trace of iron to it, the material separates into oily droplets that contain the iron. This process, called coacervation, is regarded as a "primary phenomenon" in the development of cellular structures. Giant molecules in solution have the ability to congregate or to form into droplets. They also tend to pack themselves in ordered arrays, "provided that they themselves have ordered structures."

Before leaving Calvin's account I must say a few words about another of his investigations, one having to do with the formation of the bases that constitute the nucleic acids. One can trace a sequence of chemical and physical events that might have led to living substance. Proteins and nucleic acids are the central actors both in the development of the living substance and in conferring on it the properties regarded as defining life. Self-reproduction is of course one of these properties, and it stems from the serial array of the bases in a nucleic acid, which array contains the information that directs the manufacture of proteins. It is important to know how this close and essential relation arose in the evolutionary symphony, and whether the nucleic acid or the protein came first.

An experimental approach to these questions was an attempt in the laboratory to synthesize nucleic acid bases under primitive terrestrial conditions. Electron radiation resembling that from the abundant radioactive isotope potassium 40 was used to bombard a mixture of gases believed to resemble the earth's primeval atmosphere. One product of the bombardment was hydrocyanic acid. This was not unexpected for two reasons: hydrocyanic acid is a stable compound and it is not uncommon in the universe. What was more significant was that out of the mixture containing hydrocyanic acid Calvin and his collaborator C. Palm could get the bases needed for making nucleic acids. It was already known that when hydrocyanic acid is put into a water solution with ammonia (believed to have been present in the primeval atmosphere), adenine, one of the chief bases, is formed; indeed, adenine is simply a molecule made up of five hydrocyanic acid molecules put together in a certain way. Now it was discovered that electron bombardment will produce "respectable amounts" of hydrocyanic acid, adenine and other bases. (Lightning, it has since been learned, will also do the trick.) Once again experiments had confirmed the hypothesis that certain simple substances—methane, ammonia, water and hydrogen—torn apart by ionizing radiations would recombine; that the new combinations would not be random but instead would be specific substances, some of which are the bricks of life.

The setting, then, is something like this. A large number of well-tempered planets, neither too hot nor too cold, sedately travel their stable orbits. The planets vary in size, their radii lying between 1,000 and 20,000 kilometers. Their atmosphere is benign; they are old enough to have lost much of the hydrogen that originally enveloped them, and their mass and mean density are such as to enable them to hold on to an adequate amount of the relatively heavy oxygen molecules. The stars with which they are associated are of an average sort, ranging in age between a billion and 10 billion years. These planets, it is thought, are habitable, and some of them are quite possibly inhabited by intelligent beings. It is proposed that we search for them.

There are two possible methods: signaling and space travel. The second can be disposed of without straining. In the past few years we have been exposed to both high- and low-level blather about space travel. Politicians, Government officials, military philosophers and rocketeers have been preaching the holy mission of traveling around the universe in space suits. National honor and national security are said to depend on our going somewhere and getting there first. Besides, it would be fun and the preparations are good business. Leaving aside the usefulness and feasibility of local exploration—a modest trip to the moon, say—the notion of vast space voyages belongs, the physicist Edward Purcell says, "back where it came from, on the cereal box." Both he and Sebastian von Hoerner, a German astrophysicist, expose the hoax.

Assume that a journey is planned to a nearby star—12 light-years away. We do not want to take many generations to do it so let us arbitrarily say we will make the round trip in 28 years of earth time. This means reaching a speed 99 per cent of the velocity of light in the middle of the journey, slowing down at our destination and then returning. The special theory of relativity shows that this 28-year journey will cost the voyagers only 10 years of aging time. Forget about the twin paradox; you have troubles enough (and anyway, if its implications are *not* accepted, the conclusions to be drawn from this example become, as Purcell says, even stronger).

The problem is to design a rocket to perform this mission. The elementary laws of mechanics "inexorably impose" a certain relation between the initial and the final mass of the rocket in the "ideal" case. It is plain that the propellant selected must have a very high exhaust velocity. The relation is given by this simple equation:

$$\frac{\text{initial mass}}{\text{final mass}} = \left[\frac{c + V_{max}}{c - V_{max}}\right]^{c/2V_{ex}}.$$

Here c is the speed of light; V_{max}, the rocket's maximum velocity; V_{ex}, the exhaust velocity. Obviously if V_{max} is near the speed of light, the denominator of the equation becomes very small and the exponent very large. So far, so good. Practical questions aside, we can use a nuclear-fusion propellant that burns hydrogen to helium with 100 per cent efficiency. This will give an exhaust velocity about an eighth of the speed of light. Purcell calculates that to attain a speed 99 per cent of the velocity of light from this kind of push one needs an initial mass (mostly the fuel) that is a little over a billion times the final mass of the rocket. To put up a ton, therefore, one must start off with a million tons.

This will never do. So one may as well go for broke, take the ultimate step and use the perfect propellant, namely matter-antimatter. This helps. To attain 99 per cent of the velocity of light a ratio of only 14 is needed between the initial and the final mass. But what with having "to slow down to a stop, turn around, get up to speed again, come home [if you care] and stop," the tame 14 becomes 14^4, which is some 40,000. Thus by Purcell's reckoning, to take a 10-ton payload on the 28-light-year trip requires a 400,000-ton rocket, half matter and half antimatter—the latter admittedly not easy to put in tanks.

A small point about the antimatter rocket. To achieve the required acceleration the rocket will have to radiate about 10^{18} watts near the beginning of its journey. This turns out to be "only a little more than the total power the earth receives from the sun." Purcell reminds us, however, that the rocket radiation is not sunshine but gamma rays. Therefore there are two protection problems: to shield the occupants of the vehicle and to shield the earth itself from the rocket's radiation.

Von Hoerner offers a similar item. The power-mass ratio (P) needed to get close to the velocity of light, using an antimatter photon-thrust device, comes to something like this (in units of watts or horsepower):

$$P = 3 \times 10^6 \text{ watts/gram}$$

$$= 4 \times 10^3 \text{ h.p./gram}$$

Our most efficient fission reactors, used for ship propulsion, have an output of 15,000 kilowatts and weigh 800 tons; for them P is equal to .02 watt per gram. To achieve the power-mass ratio of von Hoerner's equation the reactor can weigh no more than five grams (about the weight of ten paper clips). To express it another way, to fulfill the equation the engine of a car producing 200 horsepower cannot weigh more than a tenth of a paper clip. If 150,000 kilowatts is all one can get out of each power plant, 40 million annihilation power plants are required, plus six billion transmitting stations of 100 kilowatts each, all together having no more mass than 10 tons, to approach the velocity of light within 2 per cent within 2.3 years of the crew's time. And if, for example, one fails to fulfill this requirement by a factor of a million (so that one has "only" 40 power plants and 6,000 transmitters, weighing in all 10 tons), it would take 2.3 million years for the crew to approach the velocity of light within 2 per cent.

Communication by signals is what is left to us. Here it is at least conceivable that we might succeed without the combined help of Aladdin and the Wizard of Oz.

Should we broadcast or should we simply listen? Other worlds may be broadcasting. The science and art of electromagnetic devices are advanced and we could, for example, using a reasonably large antenna, send a 10-

word telegram a distance of 12 light-years with a dollar's worth of electrical energy (Purcell). Would our message be understood? "AUNT IDA VERY ILL COME AT ONCE LOVE WERNHER" might not be. Moreover, the reply, assuming it came, would be at least 24 years delayed. A hurry-up people like us might get impatient, or forget they had ever sent a message. What about the level of technology among our planetary listeners? Wireless telegraphy is only about 50 years old and highly discriminating receivers are very recent. If, says Purcell, "we look for people who are able to receive our signals but have not surpassed us technologically, i.e., people who are not more than 20 years behind us but still not ahead, we are exploring a very thin slice of history." By all odds it would be better to listen—although it would be well to notice that if all societies follow this practice, everyone has a long wait.

In an imaginative paper published in *Nature* in 1959, Giuseppe Cocconi and Morrison suggested a listening program. According to their assumptions there are other civilized societies. They are probably well ahead of us scientifically and therefore know at least as much about the possibilities of life on our planet as we know about life on other planets; they have for a long time been sending out signals and have been "patiently" awaiting answering signals that would make known to them "that a new society has entered the community of intelligence." It is likely that the channel they have been using is one "that places a minimum burden of frequency and angular discrimination on the detector." Appropriate to our beginner status as interplanetary readers, they can be expected to give us the equivalent of big letters, easy words, wide spacing and broad margins. With this in mind and also various technical considerations relating to background noise, the absorption of certain frequencies in planetary atmospheres and the like, the question is: At what frequency should we look for signals?

The task at first glance seems enormously difficult, but on closer examination it turns out that we are the beneficiaries of circumstance. "In the most favored radio region there lies a unique, objective standard of frequency, which must be known to every observer in the universe: the outstanding radio emission line at 1,420 Mc/sec ($\lambda = 21$ cm) of neutral hydrogen. It is reasonable to expect that sensitive receivers for this frequency will be made at an early stage of the development of radio-astronomy. That would be the expectation of the operators of the assumed source, and the present state of terrestrial instruments indeed justifies the expectation. Therefore we think it most promising to search in the neighborhood of 1,420 Mc/sec."

Cocconi and Morrison proposed the examination of certain stars within 15 light-years, lying in a direction with low background noise. About a year later the proposal was acted on. A program called Project Ozma (queen of the land of Oz) was carried on for three months with an 85-foot radio telescope at the National Radio Astronomy Observatory. The two target stars were Tau Ceti and Epsilon Eridani. No signals of extraterrestrial origin were picked up, but there was an almost unbearably exciting false alarm when, within a minute or so of turning the antenna toward Tau Ceti, unmistakably strong signals began to pour in. Soon afterward they faded and could not be rediscovered. The observer, Frank D. Drake, concluded they had been terrestrial signals, but one may indulge one's fancy if one likes. Thirty years ago Carl Størmer and Balthus Van der Pol caught similar signals that were never explained.

The search will go on. It may take decades, centuries. We may have to go out 1,000 light-years. The quest may very well fail, particularly in its present form. Optical masers have been suggested as a possible means of communication; this would entail spectral resolution to distinguish between starlight and a possible separate optical signal. As far as I know, no one has proposed enlisting extrasensory perception. Thought may travel faster than light. (It is, however, appropriate to recall J. B. Priestley's observation that those who say they are getting messages from the void are probably getting them from the void within.

We have not the remotest notion what the signals we are seeking would say. It seems to be agreed that they would have to have non-Gaussian characteristics; that is, they would have to be orderly, patterned, nonrandom. But "orderly" by the standards of very advanced beings may not be discernibly orderly by our standards. If one's life expectancy is 10,000 years, say, one may design communication patterns to unfold slowly in order to guard against dying of boredom by repetition. Morrison speculates that number sequences might be sent. A string of primes, the number pi, logarithms, an algebraic formula. This does not strike me as very imaginative. B. M. Oliver describes a fanciful way of sending bits of information that could then be decoded and rearranged into pictures. Always it is assumed that we will be treated like half-wits or small children. Morrison says he cannot conceive that our earth is the concern of the great enterprises of knowledge among "far societies" but that it falls, rather, under the aegis of a "Department of Anthropology." The prevailing motives among us for space travel tend to justify this view, and a few of the contributors to this book are silly enough to impute to the societies of other planets the same murderous impulses, military ambitions, obsessions and follies that shape our own civilization.

One thing is certain: All men will have to co-operate in this unknown journey. It is an adventure for mankind, requiring unlimited patience, the highest skill and shared good will. If signals come to us, we shall want to reply. And then in turn we must wait for signals showing that we have been heard and understood. It is the perfect, deliberate philosophical discourse. We will bequeath to our children the answers to the questions we ask. If the venture is conceived in that spirit, we may have something important to communicate.

Short Reviews

THE ELECTRON, by Robert Andrews Millikan. The University of Chicago Press ($2.45). A soft-cover reissue of Millikan's classic work that describes his wonderful researches on the unit of electric charge and the photoelectric effect, for which he received a Nobel prize in 1923. It is the 1917 edition of the book that is reprinted here—the work appeared in a revised and expanded edition in 1924 and 1925—and thus it reflects a scientific climate more hospitable than today's to the search for intuitive pictures and models of physical events. Millikan relegated the mathematical proofs to the appendix and in the text tried to catch the interest of both the physicist and the "reader of somewhat less technical training." A feature of interest in the present edition is the introduction by Jesse W. M. DuMond, a close associate of Millikan's during much of his scientific career, who gives a vivid account of his work and personality and of the general picture of research in physics during the first decades of this century. The introduction ends on a note that is grist for Jessica Mitford's mill: a description of the pinchbeck ceremonies over Millikan's body when he was interred in Forest Lawn Memorial Park as an "Immortal of the Court of Honor" by courtesy of the "Council of Regents of Memorial Court of Honor." The "Pronouncement" of the council, inscribed on a parchment scroll, was carried to the grave on velvet cushions by two page boys dressed in Louis XIV costumes.

MEDICAL HISTORY OF CONTRACEPTION, by Norman E. Himes. Gamut Press, Inc. ($7.50). The late Norman Himes, a sociologist who was much interested in problems of population and social biology, published this history in 1936 as part of a series on the medical aspects of human fertility issued by the National Committee on Maternal Health. It was justly praised as the best thing of its kind, a densely packed, scholarly and ably written survey of contraceptive techniques from 1850 B.C. to A.D. 1935. Beginning with the practices of preliterate societies, some of which are still followed with remarkably little change by primitive peoples in different parts of the world, the account moves through the techniques of antiquity in the Western world, in China, India and Japan, the contraceptive medicines and devices of the Middle Ages and early modern times, the early birth control movement in Britain and the U.S. and the advent and development of democratized birth control in many countries of the world.

A good part of the history is of course concerned with magic, with all kinds of potions and practices that were intended to prevent conception by propitiating the gods rather than by direct physical intervention. Judging by the effectiveness of these means, the gods were not impressed. Still, there were unusual mixtures and solutions that, when put in the right place, achieved the desired effect because one of their ingredients acted as a spermatocide. Moreover, certain early devices were at least partially successful on a rational basis. For example, a moistened sponge inserted in the vagina was used as a contraceptive in ancient times, and it seems that this method was known to the authors of the Talmud. By the middle of the 16th century there had come into use the most famous, and still the most widely used, of contraceptive devices, namely the condom, the earliest known published description of which is to be found in the work of the Italian anatomist Fallopius, who in his *De Morbo Gallico*, first published in 1564, described a linen sheath cut to fit the glans. It should be noted, however, that Fallopius' primary interest in the sheath was as a preventive against syphilis; in this connection it is interesting to learn that just as the disease itself was in its origins ascribed by each of several countries to one of the others (for instance, the British called it the French disease), so, on the appearance of the condom, the French called it "*la capote Anglaise*," or English cape, and the English returned the compliment by calling it the "French letter."

The book devotes much detail to the rise of the birth control movements in Britain and the U.S. Himes shows himself to be a knowledgeable and perspicacious social historian and critic in his description of this important phase in the evolution of contraception. He has ransacked an enormous literature, selected material from it skillfully, discussed the subject throughout in a liberal and humane spirit and has made it abundantly clear how universal throughout human history has been the wish to limit offspring (as well as, of course, to promote fertility). A preface to the book by Alan F. Guttmacher sketches the major developments in the field from 1935 to the present time and shows that the problem that concerned prehistoric man is more serious and acute than ever. Today, however, it is less a problem of methods than of religious bias, poverty and ignorance. Here, as is so often the case, many of man's vicissitudes are of his own making. Illustrations, a 63-page bibliography and a comprehensive index.

PREHISTORY AND THE BEGINNINGS OF CIVILIZATION, by Jacquetta Hawkes and Sir Leonard Woolley. Harper & Row, Publishers ($12.50). The first volume of a somewhat grandiose enterprise, UNESCO's *History of Mankind: Cultural and Scientific Development*, this book manages to survive the attentions and not infrequently niggling interventions of sundry consultants, specialists, panels and commissions. A curious foreword by René Maheu, the Director-General of UNESCO, informs us that the work is unique not only in the breadth of its coverage and the "decentralization of viewpoints and interpretations" but also in its authorship, which is to be ascribed not, as any sensible person would infer, to the persons named on the title page but rather to an "International Commission" of 26 members and 45 corresponding members. "It is to the Commission," says the Director-General, "therefore, and to it alone, that the full credit for this work is due." He is so carried away by this conceit that he forgets even to mention Jacquetta Hawkes and Sir Leonard Woolley, who were the scribes to whom the recording task was assigned. Everything they wrote had to be checked by specialists, who then provided their own notes and comments, all of which in turn had to be edited by other "consultants." That anyone could seriously suppose that this weird procedure would elevate the work to a new plateau of historical excellence almost surpasses belief. It has in fact done nothing of the kind, and were it not for the knowledge and proved talents of Miss Hawkes and the late Sir Leonard this would have been a poor thing indeed. The final product, however, is a scholarly (if not that, what else?) and quite detailed summary of present knowledge of the dawn of man's culture. Miss Hawkes courses from the first beginnings through the Neolithic; Woolley covers the Bronze Age and the urbanization of society. Woolley, of course, has more to work on than Miss Hawkes; in addition to the manifestations of material culture and religion he has the substance of higher crafts and industries, languages and writing systems, education, the origins of mathematics, astronomy, surgery and medicine, the fine and applied arts, music and literature. The general presentation, if not exciting, is satisfactory. The book is a trifle heavy for the common reader, but it will serve reasonably well as a reference. Good illustrations.

MATHEMATICS: ITS CONTENT, METHODS AND MEANING, VOLUME I, PARTS 1, 2 AND 5, edited by A. D. Aleksandrov, A. N. Kolmogorov and M. A. Lavrent'ev. American Mathematical Society ($17.50). These books are translations of a group of Soviet mathematical monographs whose purpose is to acquaint "a sufficiently wide circle of the Soviet intelligentsia with the various mathematical disciplines, their content and methods, the foundations on which they are based and the paths along which they have developed." Part 1 of the first volume presents a general view of mathematics, including contemporary activities, by Aleksandrov, and a fairly long section on the calculus; Part 2 discusses analytic geometry and the theory of algebraic equations; Part 5 considers functions of a real variable, linear algebra and non-Euclidean geometries. Other parts, which have not yet appeared, are to cover differential equations, functions of a complex variable, prime numbers, probability theory, computers, topology, groups and other algebraic systems. The work as a whole is certainly an ambitious undertaking, but it is hard to classify by the standards with which we are familiar. To be told that the material is accessible throughout to someone with no more than secondary school training in mathematics—unless of course he is something of a prodigy—is nonsense. This is not to deny the value of the program for both the college student and the teacher, to whom it offers within moderate compass an authoritative survey of a large part of mathematics.

STRUCTURE IN ARCHITECTURE, by Mario Salvadori in collaboration with Robert Heller. Prentice-Hall, Inc. ($13). In his foreword to this book Pier Luigi Nervi observes that Salvadori's aim is to "build a bridge between the more or less conscious intuition about structure, which is common to all mankind, and the scientific knowledge of structure, which gives a fair representation of physical reality on the basis of mathematical postulates." It must be said that he and his collaborator succeed brilliantly. Without any mathematical or technical apparatus they describe such matters as loads on structures, the properties of structural material, structural requirements, the concepts of stress, the design of tension and compression structures, the use of beams, frames, arches, grids and plates, membranes and thin-shell construction. Supporting the text are simple, clean and highly instructive diagrams. An elegant book, both enlightening and attractive in appearance.

A SHORT HISTORY OF MEDICINE, by Charles Singer and E. Ashworth Underwood. Oxford University Press ($10). A second, revised and much enlarged edition of the late Charles Singer's *A Short History of Medicine*, first published in 1928. Singer made minor alterations in the text of the first edition during successive reprintings but was never able, although he recognized the need for extensive revision, to devote the necessary time to the task. Some years ago he asked Underwood, director of the Wellcome Historical Medical Museum and Library, to undertake the preparation of a new edition and entrusted the entire work to him. For the period up to about the 18th century the original form of the book has been preserved, although additions have been made. It was evident, however, that for the period after the 18th century Singer's treatment of important scientific researches and advances in historical knowledge was entirely inadequate, and this part of the book has therefore been rewritten and greatly expanded so that at least the last two-thirds of the present edition is new. We now have a sound survey (some 850 pages long compared with 350 pages in the first edition), informed by Singer's philosophy and augmented in reference value by Underwood's contribution. Illustrations of all kinds, an appendix on Nobel prize winners and a full list of readings.

THE LORE OF SHIPS, edited by Bengt Kihlberg and others. Holt, Rinehart and Winston, Inc. ($27). A copiously illustrated glossary of every artifact that has anything to do with ships and shipping, past and present. Each of the main sections has a brief introductory commentary by a specialist in naval architecture, shipbuilding, marine engineering and kindred subjects; the principal topics include the hull, the sail, spars and rigging, propulsion, fishing, yachting, navigation and ship-handling. More than 1,550 illustrations in the form of drawings printed in 17 different colors present a variety of nautical details from bowsprits to rum kegs, ship biscuit to turbo-supercharged two-stroke diesel engines, ships' flags to ethnographical boat types, lanterns to figureheads, knots to sailing theory, charts to fishhooks, cannons to sextants, canoes to nuclear reactors. Some of the captions are descriptive and helpful, but many are only identification tags and leave the landlubber as uncomprehending and full of awe as ever.

THE SCIENCE OF ANIMAL BEHAVIOR, by P. L. Broadhurst. A Pelican Book (95 cents). A clearly written, interesting introduction to the study of animal behavior. The last chapter considers the possibility of training animals for certain practical tasks, which include such bizarre labors as pigeons inspecting finished products (for example transistors or pharmaceutical pills) on conveyer belts, birds sorting mail and chimpanzees controlling continuous manufacturing processes or driving trains. First automation, now etho-technology. Illustrations.

Notes

THE MATHEMATICAL THEORY OF COMMUNICATION, by Claude E. Shannon and Warren Weaver. The University of Illinois Press (95 cents). A soft-cover reprint of Shannon's celebrated paper on

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communication theory, first published in 1948 in the *Bell System Technical Journal.* Weaver's accompanying essay, a condensation of which appeared in this magazine in July, 1949, is a nonmathematical exposition of Shannon's concepts.

SCULPTURE AND CERAMICS OF PAUL GAUGUIN, by Christopher Gray. The Johns Hopkins Press ($22.50). A critical study, together with a catalogue *raisonné* of the known pieces of Gauguin's sculpture and ceramics—forms of his work that are less popular and certainly much less well known than his paintings. Each of the pieces in the catalogue is illustrated and there are 18 color plates. A handsome book.

ASTROPHYSICAL QUANTITIES, by C. W. Allen. The Athlone Press ($10.10). The second edition of this book that gives essential quantitative information about astrophysics in compact, readily usable form has been revised and expanded.

RUSSIAN-ENGLISH PHYSICS DICTIONARY, by Irving Emin. John Wiley & Sons, Inc. ($14). Based on the reading and translation of approximately 10,000 pages of recent Soviet physics journals and augmented by vocabulary drawn from encyclopedias, texts, treatises, dictionaries and the like. The major branches of physics are covered, there is a mathematical vocabulary and terms are included from related sciences.

DIDEROT: INTERPRETER OF NATURE, edited by Jonathan Kemp. International Publishers ($6). A republication of a thoughtful selection from the writings of the great encyclopedist, skillfully translated by Jean Stewart and Jonathan Kemp. A graceful anthology that deserves to be reprinted.

MAN AND ENERGY, by A. R. Ubbelohde. A Pelican Book ($1.25). This admirable survey by the professor of thermodynamics at the Imperial College of Science and Technology of the way man since ancient times has drawn on the earth's energy resources, and invented methods and machines for getting more, has been revised since its first appearance in 1954 to include the uses of nuclear energy. Illustrated.

CLASSICS IN THE THEORY OF CHEMICAL COMBINATION, edited by O. Theodor Benfey. Dover Publications, Inc. ($1.85). This first volume of a new series called "Classics of Science" contains nine papers representing major advances in the development of the valence concept in chemistry. Among the chemists represented are Friedrich Wöhler, Justus Liebig, Auguste Laurent, Edward Frankland, August Kekulé, Jacobus van't Hoff and Joseph Achille le Bel. Illustrations. Paper-backed.

SOLAR FLARES, by Henry J. Smith and Elske van Panhuys Smith. The Macmillan Company ($12.95). A summary of what is known about the vigorously studied subject of solar flares: their morphology, relation to other solar phenomena, spectral properties in the visual and radio wavelengths, their particle and ultrashort-wave radiations. Illustrated.

EVOLUTION, GENETICS, AND MAN, by Theodosius Dobzhansky. Science Editions, Inc. ($2.45). A soft-cover reprint of a masterly survey of evolution and its genetic basis by a noted student of biology. Suitable either as a popularization for adults or as a collateral reader for students with high school training in biology.

THE MOON, METEORITES AND COMETS, edited by Barbara M. Middlehurst and Gerard P. Kuiper. The University of Chicago Press ($15). This is the fourth volume of the University of Chicago Press's series on the solar system, a reference work containing articles dealing with every phase of the subject. It is an undertaking that merits praise on several counts: the competence of the contributors, the illustrations, the typography and design of the individual volumes.

THE ENCYCLOPEDIA OF X-RAYS AND GAMMA RAYS, edited by George L. Clark. Reinhold Publishing Corp. ($35). Some 300 specialists have written more than 350 articles for this new scientific encyclopedia, which treats of a wide range of topics from absorptiometry to the weathering of soil minerals.

INSECT PATHOLOGY, edited by Edward A. Steinhaus. Academic Press ($22). The first volume of a projected two-volume advanced treatise concerned with both infectious and noninfectious diseases in insects.

MIRROR FOR MAN, by Clyde Kluckhohn. McGraw-Hill Paperbacks ($1.95). An inexpensive reissue of a competent popular presentation of the modern science of anthropology.

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Basic Research at Sun Oil Company

Exploration: Microbes As Sophisticated Catalysts?

The scientist shown above is Dr. Ira D. Hill, Research Biochemist at Sun's Marcus Hook, Pa. Research Laboratory (B.S., Abilene Christian College; M.S., Purdue University; PhD., University of Texas; American Chemical Society; American Society for Microbiology).

Dr. Hill is engaged in an extensive study of the use of microbes as highly sophisticated catalysts in chemical reactions. Specifically, this research program is aimed at discovering how enzyme systems of microorganisms can be used to convert hydrocarbon raw materials into useful products.

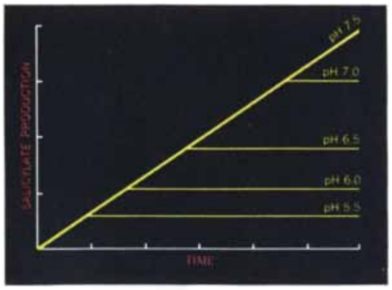
The microbiological conversion of naphthalene to salicylic acid, chosen as a model system, is typical of the investigations currently being undertaken by Dr. Hill. Naphthalene-utilizing organisms were isolated from the soil in Sun's R&D flower beds. One of these, a species designated H-30, was capable of converting naphthalene to salicylic acid at a rate convenient for study and within the bounds of commercial feasibility.

The ability of H-30 cells to catalyze the series of reactions leading to salicylic acid was measured versus a number of environmental conditions and growth period parameters. By washing the cells free of their growth liquor and resuspending them in a buffer containing none of the nitrogen compounds required for cell growth, the conversion reactions were almost completely dissociated from the normal life processes.

Under these "resting cell" conditions, it was found that many environmental factors such as pH and product concentration did not affect these particular steps in the same manner that might be deduced from a study of the conversion during cell proliferation. For example, as the pH of the "resting cell" suspension was lowered, there was no appreciable change in initial rate; however, each successive pH level reached its maximum production level in a shorter time interval.

Also, as can be seen in the graph, the change from a positive rate to zero rate is unusually abrupt, a phenomena not usually seen in fermentation systems. This abrupt characteristic, and calculations from the pKa of the salicylic acid, indicates that the observed product inhibition may be more than a simple inhibition by salicylic acid and its salts.

Dr. Hill's activities in the area of fermentation microbiology are typical of the many and varied research activities currently being carried out by hundreds of Sun scientific personnel into such subjects as electrochemistry, free radical reactions, organic synthesis and tribophysics at this and other labs across the country.



Effect of pH on the production of salicylate by resting cells.

Naphthalene-utilizing cultures are examined under a stereoscopic microscope.

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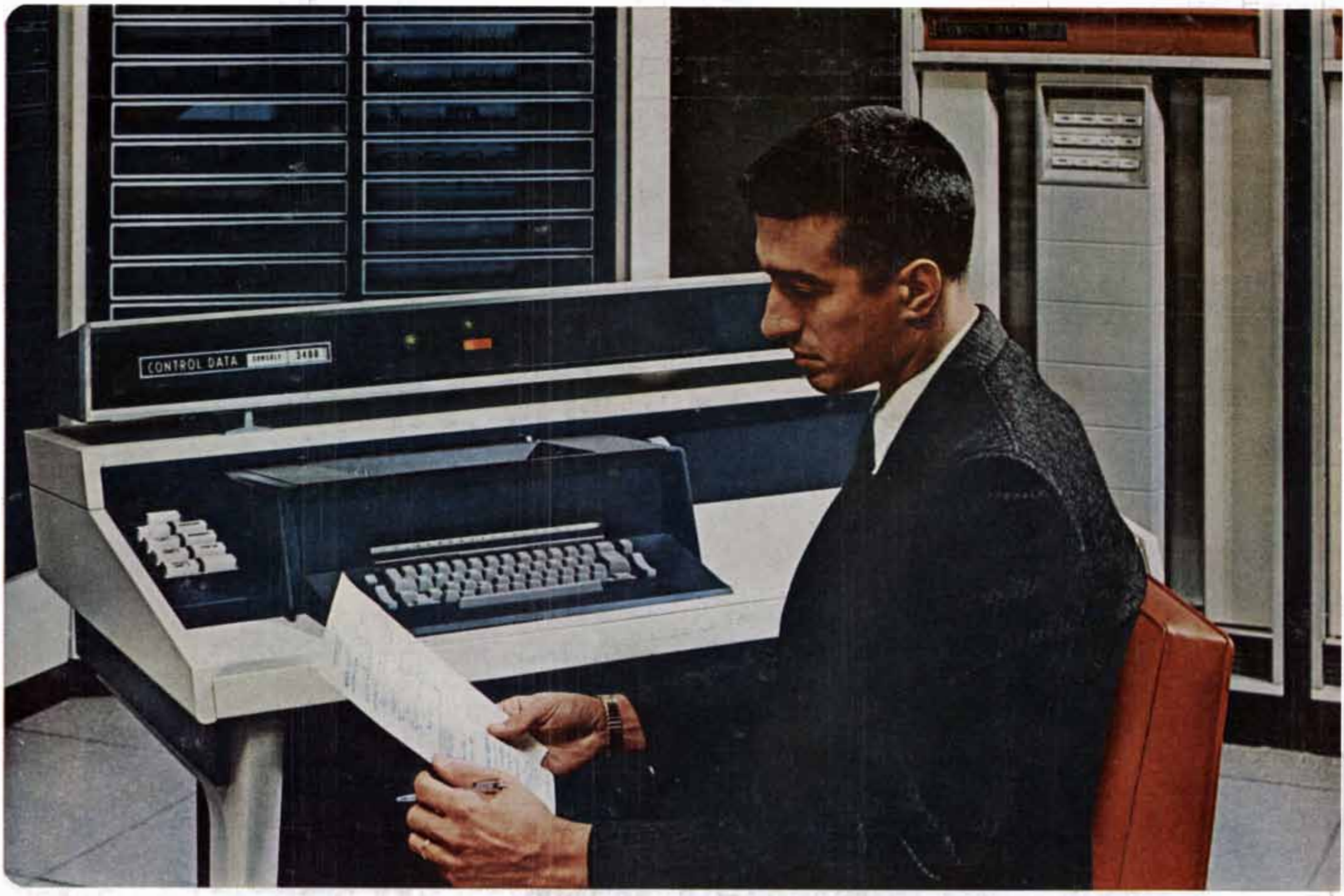

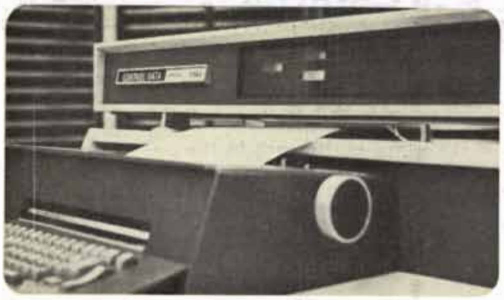

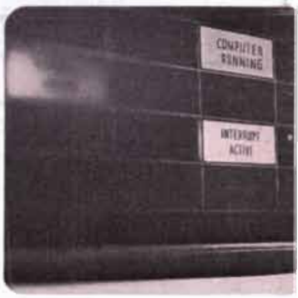

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