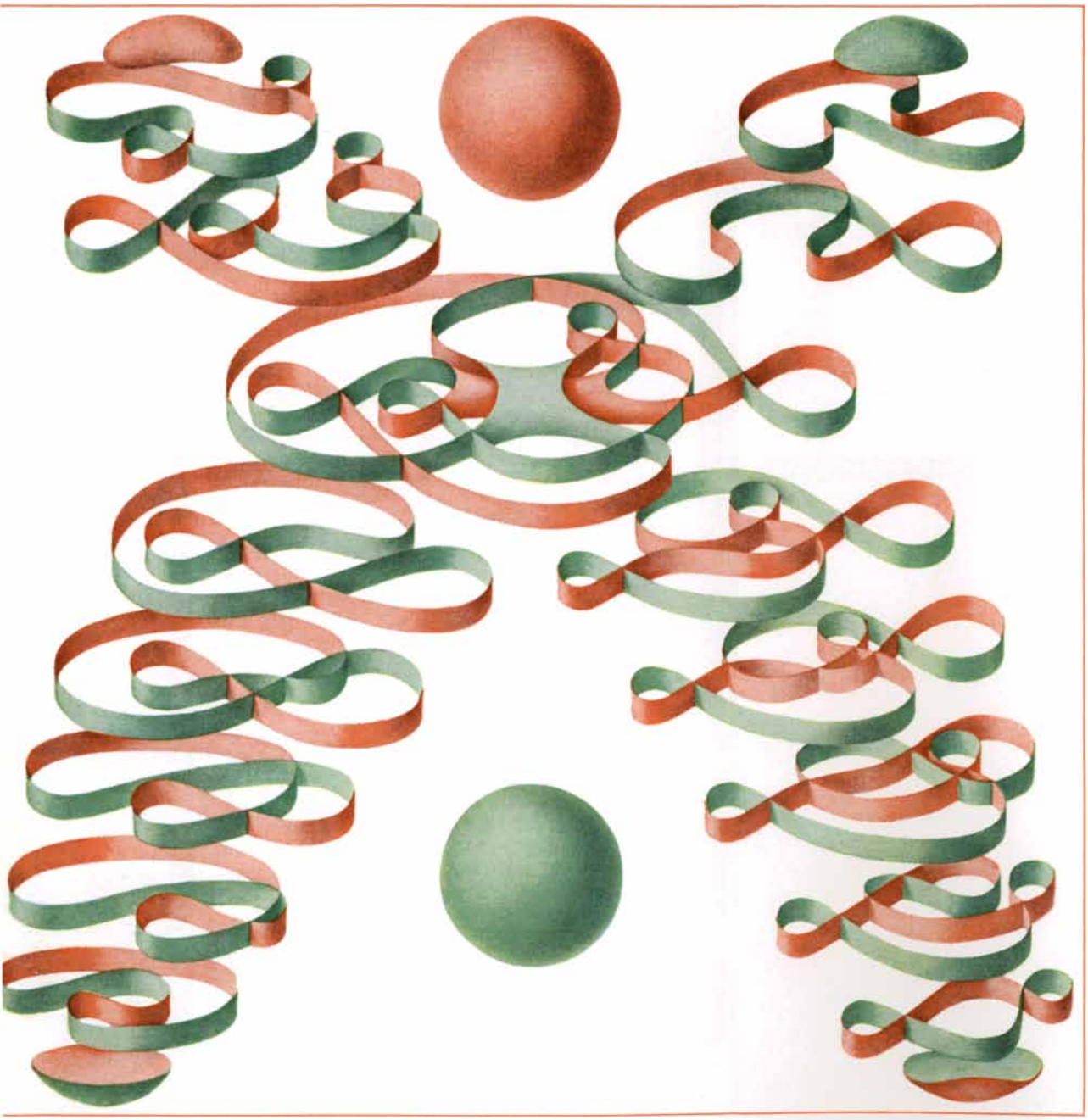
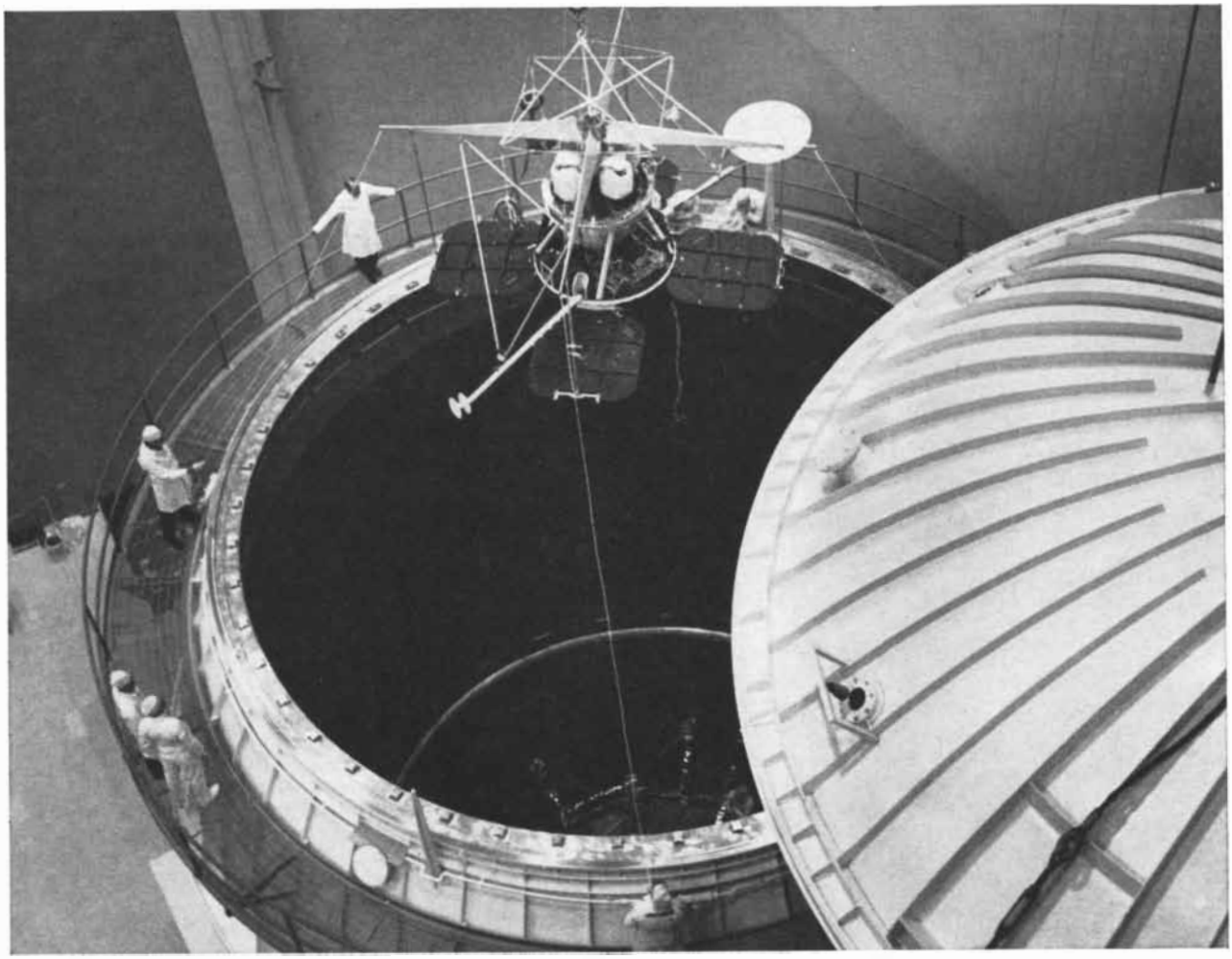
# SCIENTIFIC AMERICAN



EVERTED SPHERE

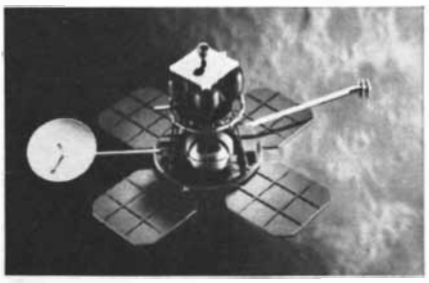
*SIXTY CENTS*

*May 1966*



**LUNAR ORBITER** camera-carrying spacecraft is being lowered into 50-foot-high space chamber at Boeing Space Center. During "flight" tests in chamber, NASA's Boeing-built Lunar Orbiter simulates a photographic mission to the moon, involving translunar journey and nine lunar orbits. The Boeing chamber simulates altitude of space and temperature extremes matching those on the dark and sunny sides of moon (minus 300°F. to plus 250°). Boeing Space Center contains ten other space environment chambers, used to test materials, components and vehicles to obtain prelaunch operating data. Solar radiation, deep space temperatures and altitudes up to 600 miles can be simulated.

# *Capability has many faces at Boeing*



**NASA's** Lunar Orbiter, seen above and in picture at top, will be launched this year to photograph large areas of moon surface to help select best landing spot for American astronauts.

**HiBEX,** high-acceleration missile booster, shown being test fired at White Sands Missile Range. Tests, sponsored by Advanced Research Projects Agency with Boeing as prime contractor, are part of a study of ballistic missile defense systems.


**NEWEST** jetliner, Boeing 737, will carry up to 117 passengers at 580 mph, and will offer more head and shoulder room than any other short-range jet. Already ordered by Braathens, Irish, Lufthansa, Mexicana, Northern Consolidated, Pacific, Piedmont, United, Western and Wien Air Alaska.

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*Ever wonder about what a steel research man wonders about?*

*Some notes on work in progress or recently completed in the research labs of one of the big steel companies.*

By Dr. Karl L. Fetters
Vice President, Research and Development for
Youngstown Sheet and Tube Co.

The curious cats in the research department of our company are continually on the prowl in examination of the thousands of problems and opportunities that surround steel—the most basic of all the basic commodities.

Simply to show you the range of our research activities I have set down here a dozen headings under which we are making investigations, with a few words about what's happening in each.

### Beneficiation and Iron Making

*Sinter Studies.* Sinter mixes consisting of varying proportions of concentrates, fines, and mill scale with and without flux additions, are being tested to determine the conditions for making high iron, low silica sinter having a high bulk density suitable for use in the open hearth.

### Carbonization

*Petrographic Studies of Coal.* Float-sink studies have been initiated on column samples of coal to determine the response to gravity separation of pyrite associated with light and heavy gravity petrographic entitles. The results will be used to develop data whereby predictions can be made on the washability characteristics of the coal by petrographic association analyses.

### Melting

*Study of the Effect of Ingot Mold Size and Steelmaking Practices on the Quality of Rimming and Bottle Top Steels.* A program has been established to investigate the quality of rimming and bottle top steels. This program includes a study of deoxidation practices, teeming speeds, and mold practices.

### Refractories

*Pouring Pit Refractories.* Work continues with ladle nozzle inserts. Initial trials of several inserts looked very promising. Work in progress now is in new nozzle sizes.

### Processing

*Continuous Casting.* Samples of blanks from an AK concast steel run have now been sheared into tensile specimens for evaluation of detailed mechanical properties of cold strip rolled from AK concast steel. Work continues on the determination of oxygen in AK concast steel at various locations in the slabs.

### Corrosion

*Corrosion of Carbonated Beverage Plate.* Results of a blue dye test on nitrogen annealed tin plate from experimental ingots containing varying sulfur concentrations to determine relationship between corrosion resistance and sulfur content.

### Coatings

*Corrosion Resistant Tin Plate.* To determine the extent of improvement in corrosion resistance of tin plate attainable by duplex plating, experiments were conducted on the halogen line by initially depositing tin coatings of .01 and .09 lb./BB; alloying same to FeSn or $FeSn_2$; and subsequently recoating both FeSn and $FeSn_2$ coatings to .25 lb./BB, .50 lb./BB, and 1.35 lb./BB tin.

Laboratory tests will compare corrosion resistance of this material with conventional tin plate of equivalent tin coating weight.

### Physical Metallurgy

*Experimental Tin Plate — Properties of Quenched and Tempered Low Carbon Strip.* Several coils of .0088″ black plate were processed with electron beam guns mainly for setting up the beam gun parameters. And to adapt the equipment to specific tests on quenched and tempered low carbon strip for experimental tin plate.

### Mechanical Metallurgy

*Formability.* Inverse pole figure determinations were carried out on the low-carbon al-killed steel given various per cent cold reduction. Studies have been conducted in the presence of recrystallization components leading to low and high $R_0$ and $R_{90}$ and Maximum R values at 45° directions.

### Operations Research and Applied Mathematics

*Seamless Round Yield Analysis.* To help analyze seamless round yield data on 5,000 keypunch cards, computer programs have been written and run to summarize and group the data in any manner desired. The purpose of the analysis is to determine the effect various factors such as conditioning practice, ingot type, size, have on the yield of seamless rounds.

### Research Services

*Boron Steel.* Forgings have been made of a heat of boron steel, grade AISI 10B48 and these are being tested for automotive application. This steel would be used as a replacement for 5150 steel.

### Research Laboratory Services

*Impact Properties of Tempered and Untempered Weld Zone.* Samples of 20-inch O. D. by 0.234″ wall, Grade X-60 electric weld pipe are being tested. These samples consisted of one which was processed normally, and two which had the weld zone left untempered. The impact properties are being determined and compared.

This is the first of a series of articles in which we'll bring you news of what's going on in steel research at Youngstown.

It is a fact that almost all of our research is "inspired" or motivated by customers' needs and we make quite a thing of offering our research knowledge to the service of our customers. It's all part of a new spirit at Youngstown, expressed in the word Steelability.

Steelability simply stated is Youngstown's capacity plus desire to meet the most strenuous demands of our customers. Research across a wide range and in depth, is a part of Steelability. If you think our researchers might be able to help you, give us a call or Write Dept. 251A6.

Established 1845 **SCIENTIFIC AMERICAN** May 1966 Volume 214 Number 5

ARTICLES



DEPARTMENTS





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## THE COVER

What appears to be a fanciful design on the cover is an actual representation of a stage in the complex process of turning a sphere inside out according to the rules of differential topology (see "Turning a Surface Inside Out," page 112). Ordinarily a sphere can be turned inside out only by making an opening in it and pulling the inside through the opening. In differential topology it is assumed that any point on a surface can pass through any other point. Until recently, however, it was believed that even under such conditions it was not possible to turn a sphere inside out without the formation of a loop of surface that would have to be pulled through itself. This would result in a "crease." In 1959 Stephen Smale, then at the University of Michigan, published a proof that the sphere could be everted without the formation of a crease. In the design on the cover the original sphere is at top center; it is pink outside, green inside. In a series of steps (detailed on pages 113 through 117) the sphere is pulled into a highly convoluted surface. Each of the ribbon-like configurations is a horizontal section through this surface. The everted sphere is at bottom center.

## THE ILLUSTRATIONS

Cover painting by Thomas Prentiss

| Page | Source |
|---|---|
| 21 | Litton Industries' Aero Service Division |
| 22–26 | Eric Mose |
| 27 | United Arab Republic Tourist and Information Center |
| 28 | Eric Mose |
| 29 | United Arab Republic Tourist and Information Center |
| 30 | Roy DeCarava |
| 31–38 | James Egleson |
| 39 | Donald N. Langenberg |
| 40 | Joan Starwood |
| 41 | Thomas Prentiss |
| 42 | David E. Scherman |
| 43–50 | Joan Starwood |
| 63–64 | Dan Todd |
| 65 | Dan Todd (*top*), Samuel L. Howard (*bottom*) |
| 66 | Jo Ann Beechel (*top*), Alex Semenoick (*bottom*) |
| 67 | Samuel L. Howard |
| 68 | Dan Todd |
| 69 | Alex Semenoick |
| 70 | Jet Propulsion Laboratory (*top*), Alex Semenoick (*bottom*) |
| 72 | Alex Semenoick |
| 77 | Enid Kotschnig |
| 78 | Hatti Sauer |
| 79 | Enid Kotschnig |
| 80 | Enid Kotschnig (*top*), William Etkin (*bottom*) |
| 82 | William Etkin |
| 84 | Hatti Sauer |
| 86 | Hatti Sauer and Enid Kotschnig |
| 88 | Ernst A. Scharrer and Stanley Brown (*top*), Jack Rosenbluth (*bottom*) |
| 92 | George F. Dales |
| 94–96 | Bunji Tagawa |
| 97 | George F. Dales |
| 98 | George F. Dales (*top and bottom right*), Archaeological Survey of India (*bottom left*) |
| 100 | George F. Dales |
| 102–103 | Bunji Tagawa |
| 104 | Bunji Tagawa (*top*), W. H. Talbot (*bottom*) |
| 105 | Bunji Tagawa |
| 106 | Victor J. Wilson and R. C. Thomas |
| 107–110 | Bunji Tagawa |
| 113–118 | Irving Geis and Allen Beechel |
| 119–120 | Allen Beechel and John Lewis |
| 122–127 | Jo Ann Beechel |
| 128–132 | Roger Hayward |
| 134 | Daniel Gordon |

# GEODOLITE™

LASER DISTANCE MEASURING INSTRUMENT

**Geodolite. Geodolite? What's that?**

A new distance measuring instrument using a laser.

**Oh?**

Accurate to within a small fraction of an inch per mile.

**Oh. Really? How does it work?**

Uses a modulated light beam from a continuous-wave gas laser; compares the phase difference between transmitted and returned beams.

**How far away? From where to where?**

Practically as far as you can see . . . point-to-point on the ground, ground-to-air, or shore-to-ship.

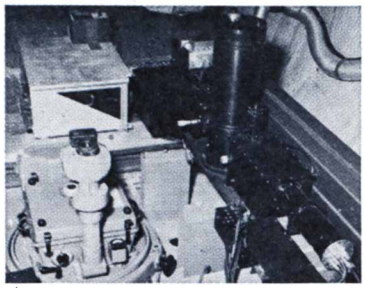
**Can it be used in geodetic applications?**

It can, for first-order geodetic surveys out to more than 50 miles, earth motion studies, precise control surveying and mapping.

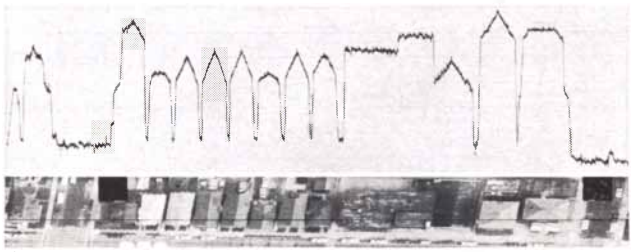
**How about such uses as aerial reconnaissance and photo mapping?**

Glad you asked. The Mark III Geodolite is light enough to go aboard any fixed or rotary wing aircraft for ground roughness determination, control point elevation measurement, ice pressure ridge height analysis, sea state determination, beach slope profiling, high resolution terrain profiling, you name it.

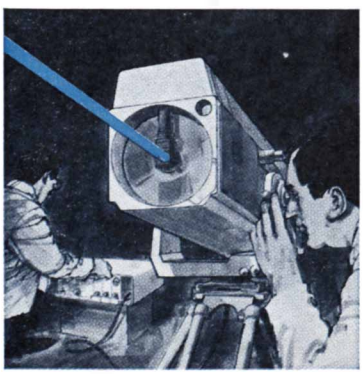
1 — Mark I Geodolite



2* — Mark II Geodolite, installed in Aero Service B-17 aircraft (instrument at right, strip camera at left)



3* — Vertical terrain profile recording made simultaneously with corresponding strip camera photo (see text)



4 — Mark III Geodolite in trunnion mount configuration

**What do you mean by high resolution?**

Take a look at Figure 3, which shows a vertical profile made with the Mark II Geodolite. It looks like a row of houses because that's what it is, recorded while flying over Atlantic City at 180 knots, altitude 600 feet.

**Will it work as an altimeter?**

Yes, to very high altitudes. And it's an excellent altimeter calibrator as well, even for high speed jet aircraft.

**What else is it good for?**

Long distance radar range calibration, short and medium distance ranging on non-cooperative targets, long distance high resolution tracking and ranging on cooperative targets, parabolic antenna mapping, practically any application where you need an ultra-precise measurement of distance.

**What is the readout?**

Analog or digital. For applications involving rapidly changing range data, an analog output is provided. For the geodetic applications, you can have a digital readout with resolution as good as 0.001 foot (also in metric units).

**What about performance specifications, reliability, and so forth?**

For the details, you'll need our new brochure G-3. Suffice it to say here that the Mark III Geodolite is a rugged, ready-to-go instrument, as practical as it is precise, as proved and reliable an instrument as you'd expect from the leading maker of gas lasers for science and industry.

**Write us today at 1247 Terra Bella Avenue, Mountain View, California for your copy of the brochure and information on price and delivery. In Europe, write Spectra-Physics, S.A., Chemin de Somais 14, Pully, Switzerland.**

Spectra-Physics

*PHOTO COURTESY OF AERO SERVICE CORPORATION, DIVISION OF LITTON INDUSTRIES

# LETTERS

Sirs:

"The Hagfish," by David Jensen [SCIENTIFIC AMERICAN, February], is most interesting. If, while in its comfortably knotted position, the hagfish reaches around and grabs its tail in its mouth, it forms a cloverleaf knot. Now, topologically speaking, there are two distinct such knots. In fact, the hagfish knot on your cover is distinct from the hagfish knots on page 83. The knot on the cover (call it, say, right-handed) is the mirror image of any of the (left-handed) knots on page 83 in the same way that a right-handed screw is the mirror image of a left-handed screw. A right-handed knot cannot be continuously deformed into a left-handed one.

Thus the question arises: Just how does a hagfish knot itself? Do there exist right- and left-handed hagfishes that always knot themselves accordingly? Or are all hagfishes ambidextrous, showing no preference for either type of knot? Do young hagfishes learn, by chance, to tie themselves in a certain kind of knot and thereafter stick to it? Or is a tendency toward one or the other type of knot perhaps inherited?

C. D. HILL
HANS RADEMACHER

Rockefeller University
New York, N.Y.

Sirs:

The subject of hagfish knotting has been most adequately covered in the excellent book *The Biology of Myxine*, edited by Alf Brodal and Ragnar Fänge, Universitetsforlaget, Oslo, 1963. I refer specifically to the chapter "The Behavior of Myxine and Other Myxinoids," by Ronald Strahan. In my own experience hagfishes do not show any particular preference for knotting in a left- or right-handed fashion; apparently the direction they take depends solely on the tactile stimulus involved and their momentary inclinations. Incidentally, when at rest in a bucket or aquarium, hagfishes seem to show no significant predilection for coiling in either a left- or a right-handed direction. Also, there is no evidence indicating that young hagfishes learn to tie themselves in one characteristic form of knot to the exclusion of the other.

With regard to the inheritance of "handedness" in knotting, the writers may be interested in "Bilateral Asymmetry and Bilateral Variation in Fishes," by Carl L. Hubbs and Laura C. Hubbs, in *Papers of the Michigan Academy of Science, Arts and Letters*, Volume 30, Part 2, 1944. Although this monograph deals primarily with structural asymmetry in the flatfishes, there may also be present in these animals a neural and cerebral asymmetry such as is found in left- and right-handed men, and this is considered an inherited characteristic. But whether or not hagfishes have achieved this advanced state of neurophysiological specialization is at the moment purely a matter for conjecture.

DAVID JENSEN

Scripps Institution of Oceanography
La Jolla, Calif.

Sirs:

I was much interested by a statement in your note "Jet Travel and Body Clocks" ["Science and the Citizen," SCIENTIFIC AMERICAN, February]: "On the outbound flights that crossed a number of time zones the passengers underwent physiological changes.... *Similar effects appeared on the return trips but did not last as long.*" (Italics mine.)

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# Ahh, to be in Massachusetts.

## With its quaint seaports, sun-swept beaches, autumn foliage, ski trails, historic shrines, and over $200,000,000 worth of industrial expansion.

The beauty of Massachusetts is an old story.

But that $200,000,000 figure may be interesting news to you. What it means is this — in 1965 alone, some 200 major new industrial plants or plant additions were completed, in progress, or announced-as-planned in this Commonwealth. Most of these are established industries that are expanding and growing with the economy. Here are a few examples: General Electric's more than $31 million modernization program in Pittsfield, Lynn, and Everett; Polaroid's $9 million program in Norwood; Itek's $4 million optics research building in Lexington. On Cape Cod, in the town of Sandwich, a $100 million power plant is being built by private utility companies. In Cambridge, NASA's $60 million electronics research center is being planned.

Education also plays a vital role in the state's expanding economy. In the past three years, the 88 major educational institutions of Massachusetts have spent more than $358 million on construction and improvements. From these institutions comes a product important to every industry in the Commonwealth: a pool of executive and scientific brain power which has done much to spark our current industrial rebirth.

In addition to unsurpassed laboratories and research facilities, Massachusetts has a quality labor force, skilled in today's needs, with a record among industrial states of fewest "days lost" through worker-management disputes.

If you plan relocation or branch operations, it's time you turned to Massachusetts. Your family, your industry will enjoy living here. For information to fit your specific requirements, write or call

**MASSACHUSETTS DEPT. OF COMMERCE & DEVELOPMENT**
**100 Cambridge Street, Boston, Mass. 02202 Telephone (617) 727-3218**

I go to Europe every year, and my experience is the opposite of this. It takes me about twice as long to return to normal, physiologically and mentally, after a westbound flight as it does after an eastbound. This raises in my mind three questions about the Federal Aviation Agency tests:

1. What were the hours of takeoff and landing of the flights selected for the experiment?
2. At what hours do those who volunteered for the test normally go to bed and get up?
3. In what country were they born and raised?

In my own case the answers are as follows:

1. I choose what I imagine are the most popular flight times, that is to say, on eastbound flights I leave in the evening and am served a late dinner immediately after takeoff. On westbound flights I leave about 1:30 P.M. and forthwith eat a late lunch. This means that on the eastbound flight I get very little, if any, sleep.
2. Normally I am asleep by 10:00 P.M. and get up at 6:30 A.M. The time difference between New York and London is, I believe, five hours. On an eastbound flight I have no difficulty going to sleep five hours earlier than my body time because I have had so little sleep the night before, and also because it is already dark in London and I wake at a New York hour. On a westbound flight, on the other hand, both the light and the habits of friends make it impossible to go to bed at 9:30 P.M. Greenwich Time, but, tired as I may be, my body clock wakes me at about 3:00 A.M. Eastern Standard Time.
3. I was born and raised in England. Psychologically, therefore, flying east means flying home.

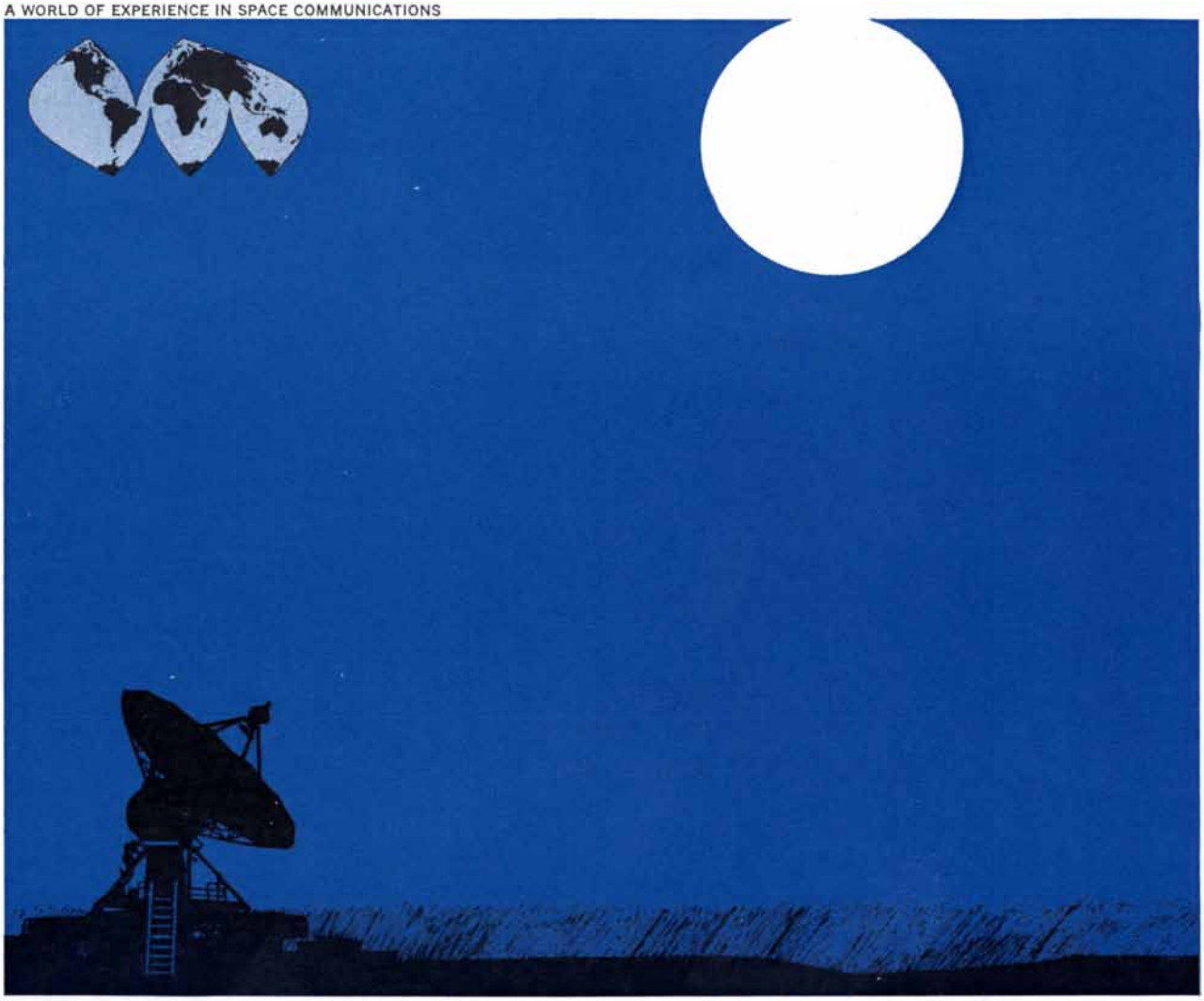
W. H. AUDEN

New York, N.Y.

### ERRATUM

In the article "The Footprints of Tumor Viruses" [SCIENTIFIC AMERICAN, March] the caption on page 35 states that the cells shown were treated with antibody to the SV 40 virus. In actuality the cells were reacted with serum from a hamster bearing an SV 40 tumor.

A WORLD OF EXPERIENCE IN SPACE COMMUNICATIONS



# How does NASA keep track of a man 238,000 miles away?

NASA's Goddard Space Flight Center has selected Collins to produce a *new* communication system for Project Apollo... Unified S Band, which will track the astronauts to the moon.

The Unified S Band concept employs a single pencil-thin radio beam to carry six kinds of communication... voice, telemetry, command, identification, rescue and television... to and from the space vehicles. The Unified S Band system will also connect all Apollo tracking stations around the world with NASA's Manned Spacecraft Center in Houston.

Collins is also providing the communication and data equipment which will be aboard the spacecraft, as well as the systems for intercommunication between the Apollo Command Module and the Lunar Excursion Module.

Every American voice from space has reached earth via Collins equipment.

Apollo will be no exception.

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# 50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1916: "The war has been a great revealer of national character, and the revelation has been full of the unexpected and surprising. Those of us who appreciated the genius of the German people for organization and efficiency, and admired that strong logical bent which enabled them to move with such directness to their great industrial and commercial accomplishments, have been dumfounded by the total lack of moral and ethical qualities as revealed in the gospel of might and frightfulness which the Germans have preached and practiced throughout the war. As evidence of this, consider the violent recrudescence of the murderous raids of the Zeppelins, whose victims are almost entirely unarmed non-combatants, at the very time when the German government professes to be endeavoring to meet the humanitarian views of President Wilson on the subject of submarine warfare. That Germany should increase her activities in the one field at the very time when she is supposed to be looking for some reasonable basis on which to diminish her activities in the other field is the latest of those many amazing contradictions that have made the civilized world ask over and over again, 'What manner of people is this?' One of two alternatives is certain. Germany, in this wholesale running amuck among non-combatants, not only of the belligerents but also of the neutral powers, is doing so either with cold-blooded but clear-headed and deliberate intent, or she is proving, on a most tragic scale, that brooding over fancied wrongs and too-long-imagined plots and persecutions may produce insanity in the nation even as in the individual."

"An instructive diagram is published in *Nature* of March 2 by Carl Störmer, which shows at a glance the distribution with respect to altitude of hundreds of auroras, determined by means of simultaneous photographs from the two stations Bossekop and Store-Korsnes during the auroral expedition of 1913. In all about 2,500 determinations of altitude are shown by dots in one small diagram. Very few dots are seen below the level of 90 kilometers, whereas a vast majority lie between 100 and 110 kilometers. An extremely small number of altitudes exceeded 200 kilometers, though three appear to have been above 300."

"After almost five months of siege the British forces under General Townshend at Kut el Amara have been compelled to surrender. This force, which originally constituted the flying column that attempted to take Bagdad, was reduced at the time of surrender to something less than 10,000 men. From a military point of view the loss of Townshend's force is of comparatively little moment; an ordinary assault at Verdun has cost far more. And it is to be doubted whether the German-led Turkish forces released for activity in other fields are sufficient to materially sway any balance; England's relief column is too close at hand to be neglected, and Russia's columns, reaching toward Bagdad from Kermanshah, are not alone, for they are supported by others north and south. The cost to England, therefore, of this, her latest failure, will probably not have to be paid during the war; but if the Entente should win in the end, the bill will be presented, for Russia would then hold the proverbial 'Nine Points of the Law,' the physical occupation of Asia Minor, to England's exclusion."

Scientific American.

MAY, 1866: "On May 5 Mr. Nobel, the Swedish engineer and inventor, who has now become famous in connection with nitro-glycerin, conducted a series of experiments at Nolte's quarry on 83rd Street in this city, with the design of showing that his blasting oil is not so dangerous as it is reputed to be. The gentlemen present, about 20 in number, appeared to be pretty well satisfied with the demonstrations, and several of them who had had previous experience on the subject seemed to fully indorse Mr. Nobel's statements."

"In a lot on the corner of Houston and Greene streets in this city Dr. Solomon Andrews of Perth Amboy, N.J., has on exhibition an aerial ship of peculiar construction which is now nearly completed, and the inventor proposes

Report from

**BELL LABORATORIES**

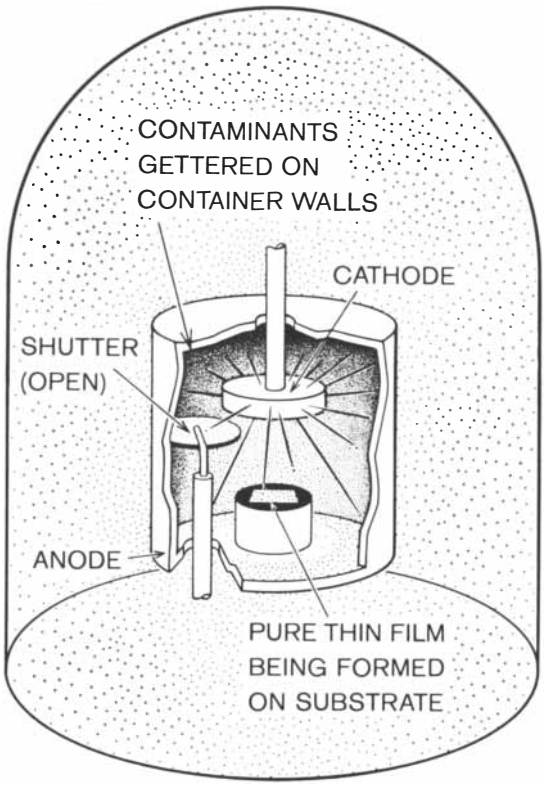
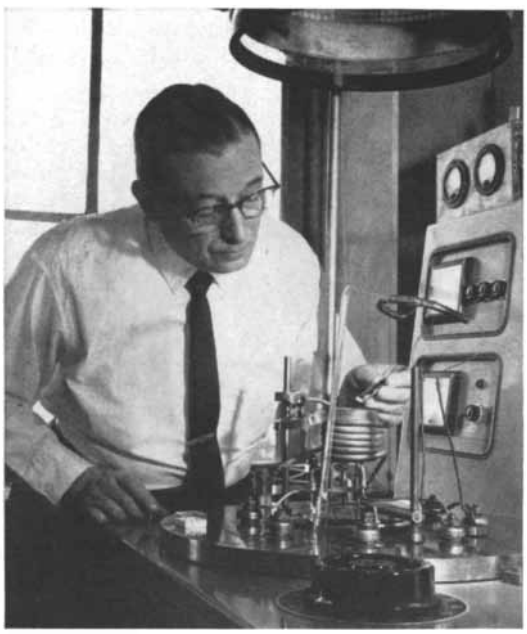



***Diagram illustrating formation of high-purity thin film at ordinary vacuum level:*** **Cathode consists of reactive metal which, transferred to substrate, forms thin film. Anode is shaped into enclosing cylinder. Surrounding atmosphere consists of argon and unwanted contaminants. When 1500-volt potential is applied, ionized argon "sputters" metal from cathode. During sputtering, metal atoms "getter" the contaminants—i.e., remove them from surroundings and hold them at the container walls. Then a protective shutter is swung aside (as shown here) and pure, uncontaminated metal travels from the cathode to the substrate to form the film.**

# High-purity thin films



**H. C. Theuerer of Bell Laboratories prepares to place a thin-film substrate in getter sputtering equipment.**

Very thin films of metal offer many opportunities for achieving small high-performance, high-reliability electronic circuits. And the technology has now reached the point where numerous problems related to thin films are being solved.

One of these problems was contamination of the films during preparation. At ordinary levels of vacuum, enough contaminants remained in the surrounding atmosphere to harm the characteristics of the film. Yet establishing an ultrahigh vacuum is expensive and time-consuming.

A solution was found by H. C. Theuerer at Bell Telephone Laboratories. It consists of letting reactive metals do double duty. As shown in the drawing, the same metal that forms the film also removes the contaminants from the atmosphere. With the new process, known as "getter sputtering," film purities that formerly required a $10^{-12}$ Torr vacuum can now be achieved with $10^{-6}$ Torr equipment.

**Bell Telephone Laboratories**
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# THE AUTHORS

ROBERT P. AMBROGGI ("Water under the Sahara") is a senior hydrogeologist with the Food and Agriculture Organization of the United Nations. A French citizen of Corsican origin, he received his undergraduate education at the University of Nancy and took a Ph.D. at the University of Paris (the Sorbonne). From 1942 to 1961 he was with the Moroccan government as director of its Groundwater Center and Water Resources Department. In addition to his work with the FAO he serves as a consultant to the UN Development Program. He has undertaken missions as a consulting hydrogeologist in Latin America, Africa, the Middle East and the Far East.

DONALD N. LANGENBERG, DOUGLAS J. SCALAPINO and BARRY N. TAYLOR ("The Josephson Effects") are in the physics department of the University of Pennsylvania, where Langenberg and Scalapino are associate professors and Taylor is assistant professor. Langenberg, a graduate of Iowa State College, received a doctorate at the University of California at Berkeley in 1959. Scalapino was graduated from Yale College and obtained a Ph.D. at Stanford University in 1961. Taylor is an alumnus of Temple University and took his doctoral degree at the University of Pennsylvania. Langenberg writes: "Scalapino is the theoretician of the trio. He is currently on leave at the University of California at San Diego and can be found there either thinking about many-body problems of solid-state physics or skin diving at a depth of several fathoms in the Pacific. Langenberg also works on microwave cyclotron resonance and related effects in metals and whenever possible indulges himself in amateur photography and an interest in the history of Anglo-Saxon England. Taylor has for the past six years devoted himself entirely to research in electron tunneling. Besides indulging in amateur astronomy, he has been known to collaborate enthusiastically with Langenberg in practical jokes on Scalapino."

JACK SCHUBERT ("Chelation in Medicine") is research professor of radiation chemistry in the Graduate School of Public Health at the University of Pittsburgh. Before taking that position in 1964 he spent three years as visiting professor at the University of Buenos Aires and consultant to the Atomic Energy Commission of Argentina. From 1948 to 1961 he was at the Argonne National Laboratory. Schubert, who was graduated from the University of Chicago in 1940 and spent some of the war years with the Manhattan project, turned in 1945 to the application of inorganic and physical chemistry to biological problems. He is the author or coauthor of numerous publications, including several books, and holds patents in radiochemical separation processes.

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WILLIAM ETKIN ("How a Tadpole Becomes a Frog") is professor of biology at the City College of the City University of New York and visiting research professor of anatomy at the Albert Einstein College of Medicine at Yeshiva University. Although his association has been mainly with City College, from which he was graduated in 1928, he has also done graduate work at Cornell University and at the University of Chicago (where he obtained a Ph.D. in 1934) and has done research in endocrinology at the American Museum of Natural History. Among his recent publications are a textbook, *Social Organization among Vertebrates*, and three theoretical papers on human evolution and the origin of culture. He is developing an introductory course in biology at Yeshiva College; he writes that its aim "is to bring out the significance modern biology has for an understanding of the entire phenomenon of man."

GEORGE F. DALES ("The Decline of the Harappans") is assistant professor of South Asian archaeology at the University of Pennsylvania and cura-


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tor in charge of the South Asia section of the University Museum. He received a doctor's degree from the University of Pennsylvania in 1960 and was on the staff of the Royal Ontario Museum in Toronto before returning to Philadelphia. Dales has participated in American and British archaeological expeditions in the Middle East since 1955; he has been directing archaeological fieldwork in South Asia, particularly West Pakistan, since 1960.

VICTOR J. WILSON ("Inhibition in the Central Nervous System") is associate professor at Rockefeller University. After obtaining bachelor's and master's degrees at Tufts University he spent a year at the University of Cambridge and then went to the University of Illinois, where he took a Ph.D. in physiology in 1953. That fall he joined the Rockefeller Institute, only to be called to Army service three weeks later. He spent most of his military service in the department of neurophysiology at the Walter Reed Army Medical Center. "It was there," he writes, "that I began experiments on the mammalian central nervous system." Wilson returned to the Rockefeller Institute in 1956.

ANTHONY PHILLIPS ("Turning a Surface Inside Out") is instructor in mathematics at the University of California at Berkeley. He writes that after an "uneventful childhood" in New York City he was graduated from the Massachusetts Institute of Technology, where he majored in mathematics, "but I also worked on machine translation and am still interested in languages and linguistics and in the psychology and physiology of perception." Phillips spent two years as a Fulbright scholar in Paris, studying topology and differential geometry, and three years as a graduate student at Princeton University, from which he expects to receive a Ph.D. this spring. He wrote his doctoral thesis on "regular maps, treating the case where maps go from higher to lower dimensions," and he is continuing in that field at Berkeley. His father is curator of western European art at the Metropolitan Museum in New York; Phillips says "maybe that explains why I like to draw pictures."

DAVID HAWKINS, who in this issue reviews *Unsafe at Any Speed: The Designed-in Dangers of the American Automobile*, by Ralph Nader, is professor of philosophy at the University of Colorado.

*Leonhard Euler*
*(1707-1783)*

*Woodcarving by William Ransom*
*Photographed by Max Yavno*

EULER ACKNOWLEDGES VIRGIL – "Euler, however, did not lose sight of the mathematics even in reciting the verses of Virgil. Everything concurred to present him with this darling object of his thoughts, and we find among his works an ingenious memoir on a question in mechanics the first idea of which, he tells us, was suggested by a line of Virgil."[1]

[1] Condorcet, quoted by Henry Hunter in *Letters of Euler to a German Princess,* London, 1795.

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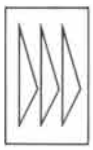

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# Water under the Sahara

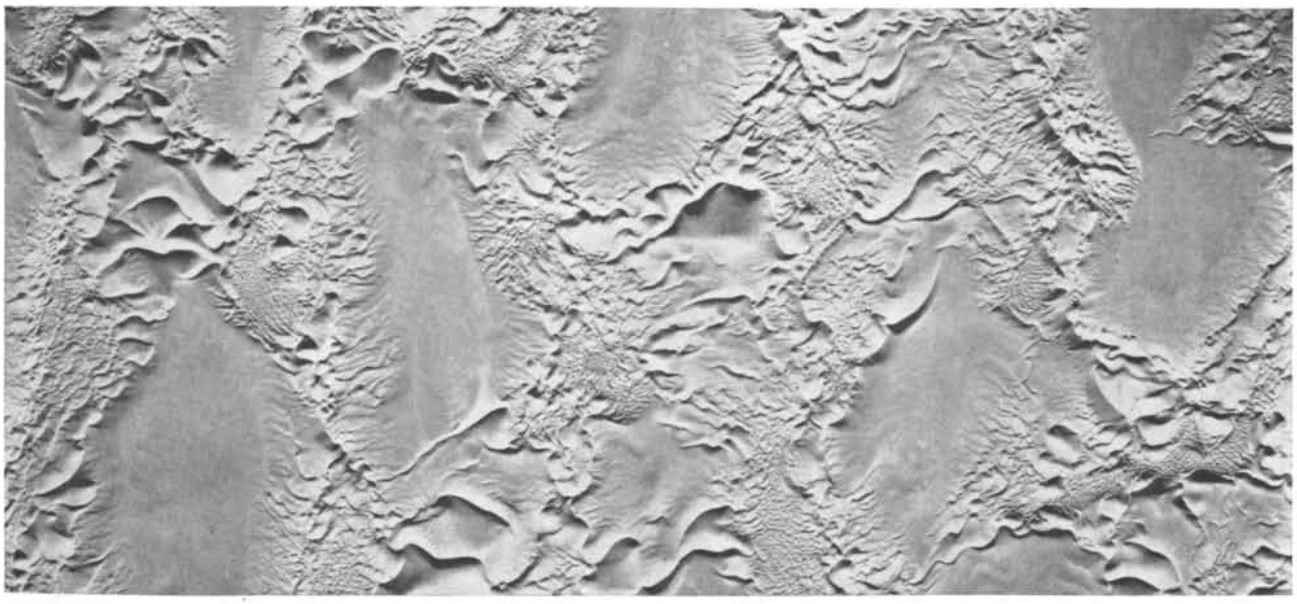
*Below the arid surface of the great desert are huge natural reservoirs of water. These resources are now beginning to be studied and exploited for the benefit of the Saharan nations*

by Robert P. Ambroggi

The Freedom from Hunger campaign being waged by the Food and Agriculture Organization of the United Nations is also a campaign against thirst. Much of the world's food problem is concentrated in the arid countries, where land, plants, animals and people are parched for water. At the center of the "arid zone" in the lower latitudes is the great desert of the Sahara. Thirteen countries with 148 million inhabitants share this vast territory and the deprivation that its name implies. The Sahara, however, possesses in abundance the remedy for aridity. Below the desert sands in water-bearing rock formations are huge quantities of water to sustain human settlement, pasturage for livestock and, in many places now barren, productive agriculture.

Oases supplied by artesian wells that have been flowing copiously since ancient times have testified to the existence of this resource. Still, men have only recently become aware of the vast dimensions of the subterranean reservoir below the Sahara. Oil prospectors found the first indications of its true extent; indeed, Saharan oil can supply the energy needed to pump the water. Good soils are also available; recent investigations have shown that extensive tracts of desert land have arable (and once cultivated) soils overlain by a thin cover of sand.

Once the Sahara was a tropical region with heavy rainfall, substantial rivers and abundant vegetation. Tools made in Neolithic and Paleolithic times



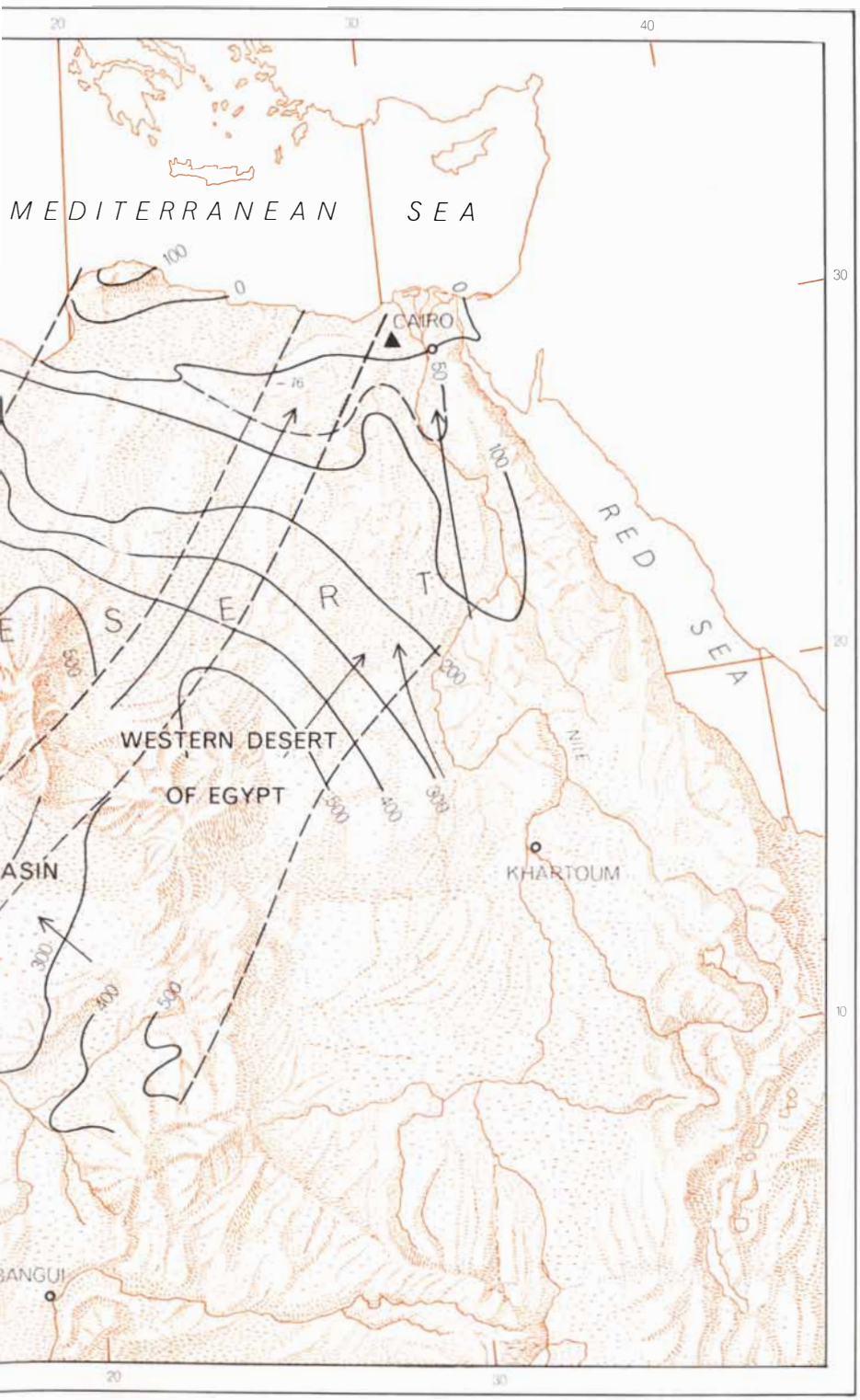
**DUNE REGION of the Sahara Desert in Libya is typical of the desert's surface barrenness. Yet this is one of the areas believed to have large stores of water in underground rock formations. With wise use of such water parts of the desert could be made to bloom.**

have been found in many places, giving evidence of widespread occupation by men. The famous rock carvings of the Tassili Mountains in the Algerian desert display a variety of animals, together with scenes of people dancing, fishing and hunting. Indications of irrigation some 8,000 years ago show that crop production continued even after the climate began to change. Today the Sahara itself, with fewer than two million inhabitants, is the least populated area of the world outside of the polar regions. The major part of the population lives in marginal steppes to the north and south and in the uplands of the Ahaggar and Tibesti mountains. Men can live in the Sahara thanks to the camel, nomadic livestock raising, caravan trade in meat and salt and irrigated cultivation practiced in the oases. Over


**SAHARA DESERT** covers an area almost as large as the U.S. Its underground water resources are mainly in seven large basins: the Great Western Erg, the Great Eastern Erg, Fezzan, Tanezrouft, the Western Desert of Egypt, Chad and Niger. The contour lines trace out zones of equal pressure in the artesian aquifers, meaning those where the water is under pressure because it is confined between underlying and overlying rock formations that are impermeable to water. The arrows show the direction of movement of water in aqui-

the past 100 years, however, the drying up of the climate has been driving human settlement from the desert proper.

There are no technological barriers to the prospect that the Sahara in many places and over large areas may now be made to bloom. The problems to be resolved in exploiting its huge resources of water are mainly political. The vast underground aquifers are geologic features that cut across national boundaries. In the interests of logic, efficiency and conservation the groundwater resources should be evaluated on a Sahara-wide basis and their use should be planned to apportion the benefits equitably among all the nations involved. These efforts have already benefited from technical assistance; the exploitation of the resource would benefit greatly from capital assistance.




**fers; this movement is usually slow and often covers long distances, so that water entering the desert from the periphery may take many centuries to reach the natural discharge areas. Such areas are indicated by diamond-shaped symbols. Besides its artesian aquifers, the Sahara has substantial stores of underground water in water-table, or pressureless, aquifers.**

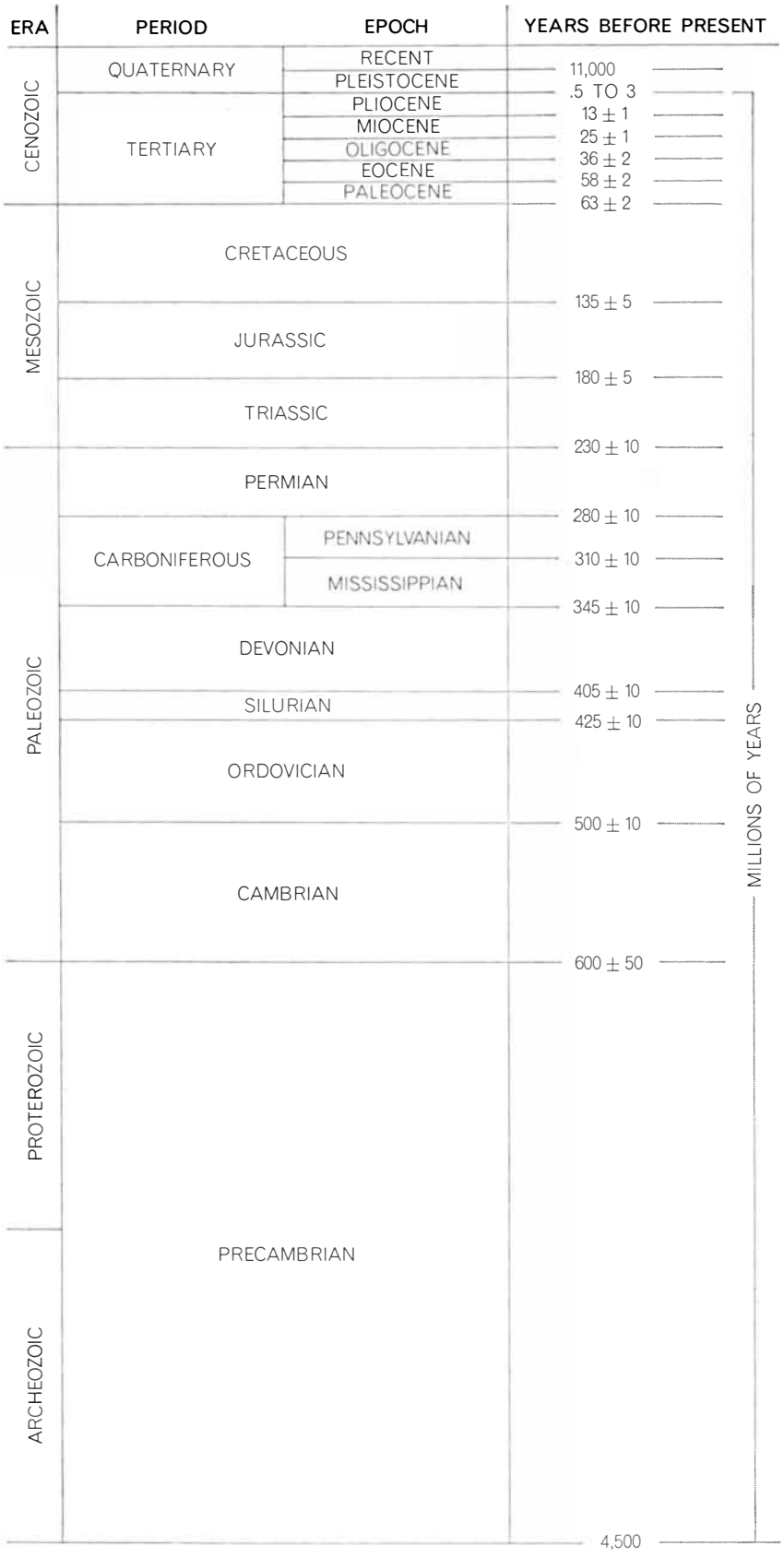
The Sahara is the world's largest desert. Its area is some 3,089,000 square miles; the area of the entire U.S. is not much larger. It stretches across North Africa for 3,000 miles from the Atlantic Ocean to the Red Sea. (Indeed, the desert continues beyond the Red Sea into Arabia, but that part of it is not called the Sahara.) Geographically the Sahara constitutes a complete break between the lands of Africa that lie along the Mediterranean Sea and the rest of the continent.

Except where the Sahara meets the Red Sea and the Atlantic, its boundaries are somewhat imprecise. They coincide approximately with the contour line that traces out the areas with an average annual rainfall of 100 millimeters (about four inches). Within these limits the rainfall can be as little as 25 millimeters a year. The rainfall is notably irregular; sometimes a large region will have no precipitation for 10 years and then the region may have several rainstorms in a year. In summer the daytime temperature is often as high as 120 degrees Fahrenheit in the shade.

In the light of the fact that the only source of water for an aquifer is rainfall, which either percolates directly into the aquifer or reaches it indirectly through streams, the existence of substantial stores of water in Saharan aquifers at first seems a paradox. The explanation is geological. Most of the water now in the aquifers was laid down in past millenniums during pluvial periods when the Sahara had substantially more rainfall than it does now. Even today, however, the aquifers are recharged to a considerable extent by rain falling at the periphery of the desert.

The full extent of the Sahara's groundwater resources remains a matter of conjecture; specialists are only beginning to understand the disposition and volume of the tremendous reservoirs. Part of this information has been acquired in the process of the explorations that led to and have followed the discovery of oil in the Sahara. Part comes from a moderate amount of hydrogeologic prospecting that has been carried out in the desert during the past decade.

The groundwater of the Sahara is to be found mainly in seven major basins,




**CHRONOLOGICAL RELATION** of three major water-bearing formations in the Sahara can be ascertained from this geologic time chart. The first is a sandstone series of lower Cretaceous age, resting on Paleozoic or Precambrian rocks. The second is a sandstone series of Miocene-Pliocene age. The third is in various formations of Pleistocene and Recent age.

each virtually a closed hydrologic system. They are the basins of the Great Western Erg and the Great Eastern Erg in the north, of Fezzan and Tanezrouft in the central region, of the Western Desert of Egypt in the east and of Chad and Niger in the south [*see illustration on preceding two pages*]. Together these seven basins have a capacity of some 15,000,000 million cubic meters of groundwater. Their total recharge is probably more than 4,000 million cubic meters a year. Although each of these basins has individual characteristics, the basins also have much in common in their geology, in the mechanisms that govern the underground flow of their waters, in the crucial question of recharge and in the problems of development.

The major aquifers are found in three kinds of formation, two of which are geologic series: a related group of rocks formed in a particular period or epoch. One of the series is the main geologic feature underlying the Sahara: a sandstone series that recent oil explorations have shown to be of lower Cretaceous age [*see illustration at left*]. This sandstone, which in many places is interbedded with shale and marl, is more than 1,000 meters thick and rests on Paleozoic or Precambrian rocks that are impervious to water. The French name for it is the Continental Intercalaire; the English, the Nubian sandstone. It constitutes an excellent aquifer.

Overlying this sandstone series is a limestone and marl series of marine origin, dating from periods when much of the Sahara was under water. About 1,000 meters thick, it is of upper Cretaceous and lower Eocene age and almost impervious to water. Above it lies the second major aquifer formation: a sandstone series of Miocene-Pliocene age. This series, also about 1,000 meters thick, is called the Continental Terminal and represents the second important aquifer of the Sahara. The third class of aquifer is represented by sand dunes, riverbeds and other surface formations dating from the Pleistocene and Recent epochs.

Water occupies an aquifer under one or the other of two distinctly different conditions. If it is overlain by an impermeable stratum, it is likely to be under pressure that will cause the water to rise above the top of the aquifer when the aquifer is penetrated by a well. This is the condition described as artesian; the term is used whether or not the water rises high enough to flow at ground level. A large part of Saharan

groundwater is under artesian conditions. If the water in an aquifer is not confined by an overlying impermeable stratum, it is said to be under water-table conditions. Such water is not under pressure and can be extracted only by pumping or gravitational flow through underground canals.

Groundwater is seldom immobile in an aquifer. Artesian water in particular is likely to move over considerable distances from a recharge area. This movement is attributable to gravity. In the Sahara evaporation is also a powerful mechanism of vertical movement: it operates as a huge pump to lower the head of the groundwater.

Evaporation from surface water can entail a discharge of more than 10,000 cubic meters a day per square kilometer. The effect is smaller, of course, for water lying below the surface. In the Sahara, however, evaporation continues to have a significant effect at depths of 20 meters or more. If this subsurface evaporation were only between a thousandth and a ten-thousandth of surface evaporation (the figure is a matter of speculation for want of sufficient data), it could still represent a loss of as much as 3,000 cubic meters a year per square kilometer.

Evaporation, which probably accounts for the largest discharge from the aquifers, takes place in vast depressions called chotts. Under the more normal climatic conditions of the past a chott would be a lake recharged by both rainfall and the artesian aquifers. Today the chotts are dry except during periods of rain.

In this connection there arises an interesting possibility of prospecting for water by zoological means. Experts in the behavior of the desert locust say that these insects need a humid environment for the laying and hatching of their eggs. In the Sahara one can observe locusts laying eggs in areas that are apparently dry. Evidently they are detecting the invisible outlets of the aquifers—the areas of evaporation. Close attention to the egg-laying habits of the locusts could conceivably lead to new sources of accessible groundwater.

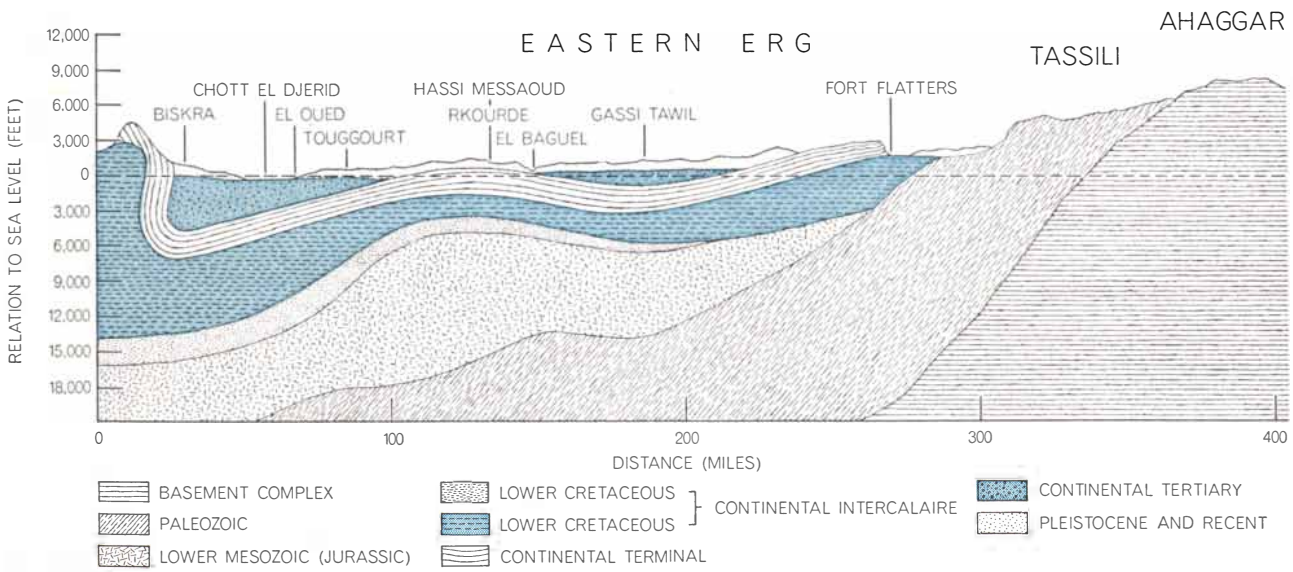
The question of recharge has to be considered in two aspects. One concerns the recharge that is occurring at present; the other, the recharge that took place long ago. Today's recharge occurs mainly at the edge of the desert, where the rainfall increases over a relatively short distance from 100 millimeters a year to 1,000 millimeters and where the water of rivers percolates into the aquifers. As far as recovery of the water is concerned, the present recharge is immediately significant only for aquifers in which the discharge and recharge areas are close together or in which the aquifer formation outcrops (is exposed at the surface). This situation exists in the Great Eastern Erg and the Niger basin.

In all the other basins the present recharge moves through the aquifers quite slowly. The speed of this movement is unlikely to be more than half a mile a year; in some places it is only a yard or two a year. This means that in most of the basins the present recharge will not reach the discharge area for 15 centuries or more. In other words, the water coming out of those discharge areas today is rain that fell between the last Saharan pluvial period and the time of the Roman Empire!

Accordingly the question of greatest interest in the modern exploitation of Saharan groundwater is what kind of recharge was occurring some 2,000 years ago. Étienne A. Bernard of the University of Louvain has undertaken to investigate this question by examining long-term changes in three aspects of the earth's motions around the sun. These aspects are the obliquity of the earth's orbit (the angle between the plane of the orbit and the plane of the Equator), the eccentricity of the orbit (its departure from the circular) and the position of perihelion (the point in the orbit at which the earth comes closest to the sun).

Bernard's investigations indicate that the periods of heaviest rainfall in the Sahara coincided with times when the obliquity was large, the eccentricity was at a maximum and perihelion occurred at a time of year when its effect would be to moderate both the winter and the summer climate of the Sahara [*see bottom illustration on page 28*]. These were the interglacial periods: the periods between the major glaciations. During such periods the continental ice sheets retreated somewhat.

This hypothesis reinforces a theory of geologists that the periods of reduced glaciation in higher latitudes corresponded with periods of heavy summer rainfall in the Sahara—rainfall at an annual rate of perhaps 600 millimeters. Hence during the pluvial periods, which totaled some 140,000 years during the million-year span of the Pleistocene, the recharge of Saharan aquifers was far larger than it is today. When

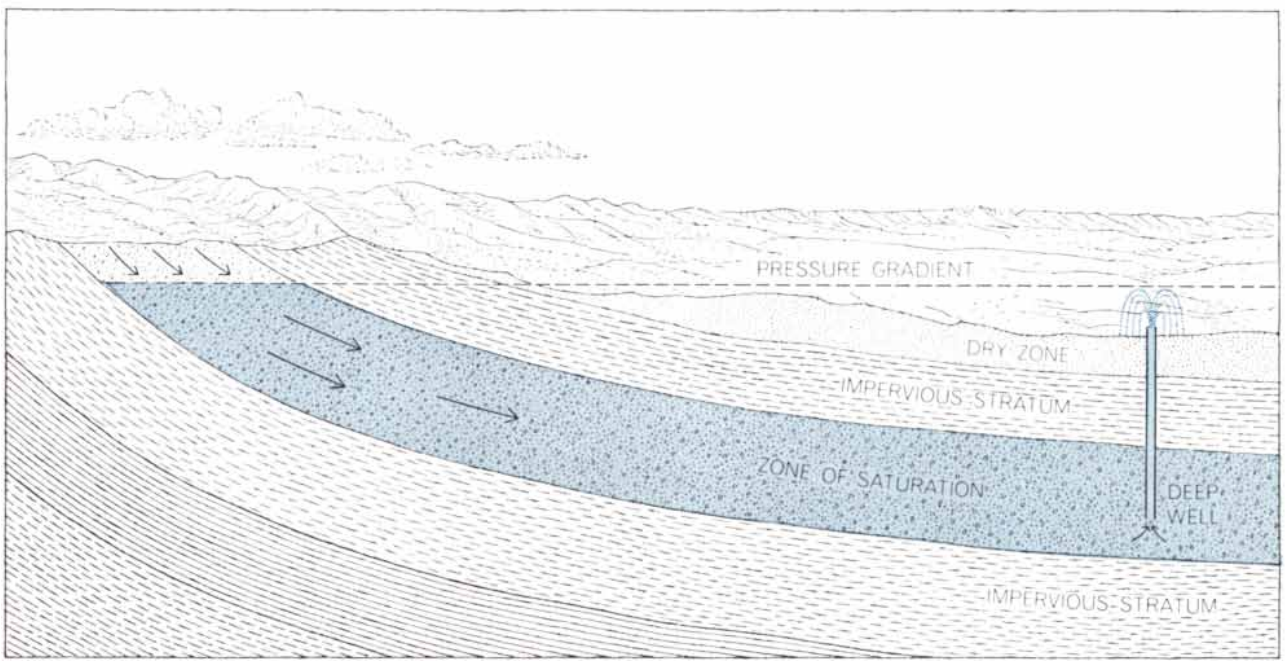



**GEOLOGIC PROFILE** of a section of the Great Eastern Erg includes an area from the Atlas Mountains (*left*) southward to the Ahaggar Mountains. Groundwater is in two major geologic formations (*color*) and in such surface features as dunes and riverbeds.

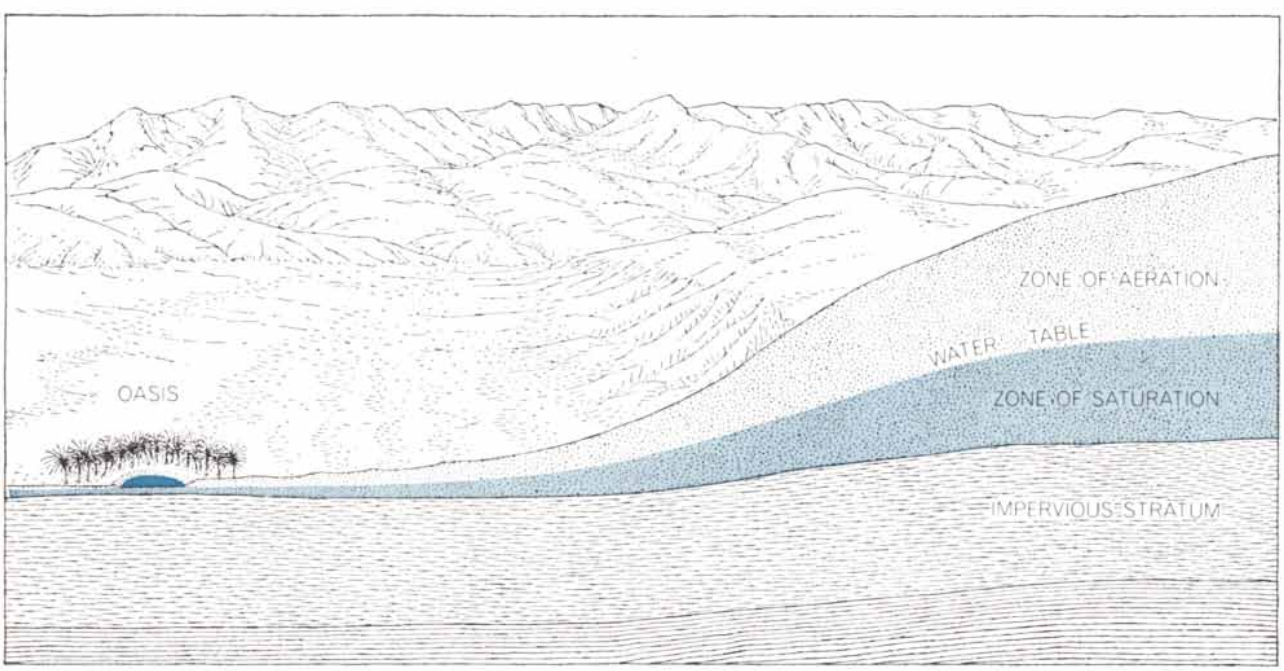
rainfall is more than 400 millimeters a year, the aquifers receive some direct recharge from the rain; in addition they were infiltrated in ancient interglacial times by the large amounts of surface water that had accumulated during the rainy epochs. In this way the aquifers were gradually filled, even to the point of outcropping in the form of large lakes. Lake Chad at these times became a vast inland sea of fresh water.

The infiltrated water was deposited in the water-bearing formations in layers. Under water-table conditions, and even to a considerable extent under artesian conditions, such a layer tends to persist rather than to mix with other layers. Hence it is possible to establish the age of the water according to its stratification.

For this purpose the technique of radioactive dating has recently been applied. The technique is based on the groundwater's content of tritium, carbon 14 or naturally occurring isotopes of uranium and thorium. Natural tritium is suitable for dating relatively young groundwater, with an age of less than 100 years, although the process has been complicated by the tritium in-




**ARTESIAN CONDITION of water in an aquifer occurs when the water-bearing rock has impervious formations below and above it. The water is therefore under pressure and will rise above the top of the aquifer, perhaps even to or above ground level, if the aquifer is penetrated by a well. After water has entered the aquifer from a recharge area (*left*) the artesian pressure increases with depth.**




**WATER-TABLE CONDITIONS in an aquifer exist when the water is not confined between impervious strata. Hence it is not under pressure and can be extracted only by pumping or gravitational flow unless it is outcropping, as depicted in the oasis shown here.**

troduced into the atmosphere since 1952 by the testing of hydrogen bombs. This tritium has entered Saharan groundwater in pulses, a fact that can be used in tracing the movement of the water and in recent dating but that tends to confuse attempts at dating over a longer period.

Carbon-14 dating is suitable for dating older groundwater. The results so far, however, are somewhat inconclusive, partly for the lack of sufficient data and partly because the uncertainty in the determination of an age can range from 1,300 to 5,700 years as a result of the fact that the water in the Nubian sandstone has a small content of carbon. The sources of the carbon are dissolved carbonate, carbon dioxide in the air and plant carbon from the decay of organic matter in the soil. The age of the oldest water yet tested is about 25,000 years; it was found in the Western Desert of Egypt.

**ARTESIAN WELL spouts water high above the desert in the United Arab Republic's New Valley project. The project involves the drilling of more than 200 boreholes, each several hundred yards deep, into a sandstone aquifer to produce water for making the desert fertile.**

Any consideration of the development of Saharan groundwater should begin with an estimate of present consumption. The level of consumption appears to be about 2,000 million cubic meters a year. Only a small part of this goes to the supply of human communities, and the needs in that area should be easy to supply even if the population increases 2 percent a year. Similarly, the needs for the watering of livestock—the chief requirement of the desert's nomadic population—should present no problems of supply. The difficulty here is to create an adequate network of wells and to induce the nomads to curb the hostility that often leads one clan or tribe to destroy another's wells. Even the expanding oil industry is unlikely to make serious demands on the desert's groundwater resources.

The largest consumption of groundwater is for irrigation. Here the demand is already pressing hard on the supply in some areas and seems likely to do so in others. To a considerable extent this situation is attributable to the wasteful and inefficient irrigation methods practiced in most of the oases. A strong case can be made for the argument that sound agricultural and irrigational practices should be introduced before any effort is made to develop new supplies of groundwater or to extend oases.

Under present practices the requirement for irrigation is about one liter per second per hectare. That is roughly equivalent to one quart per second over two and a half acres. With sound practices the traditional three-layer growth in an oasis—vegetables growing under fruit trees, which in turn grow under an umbrella of palm trees—could be irrigated with appreciably less water.

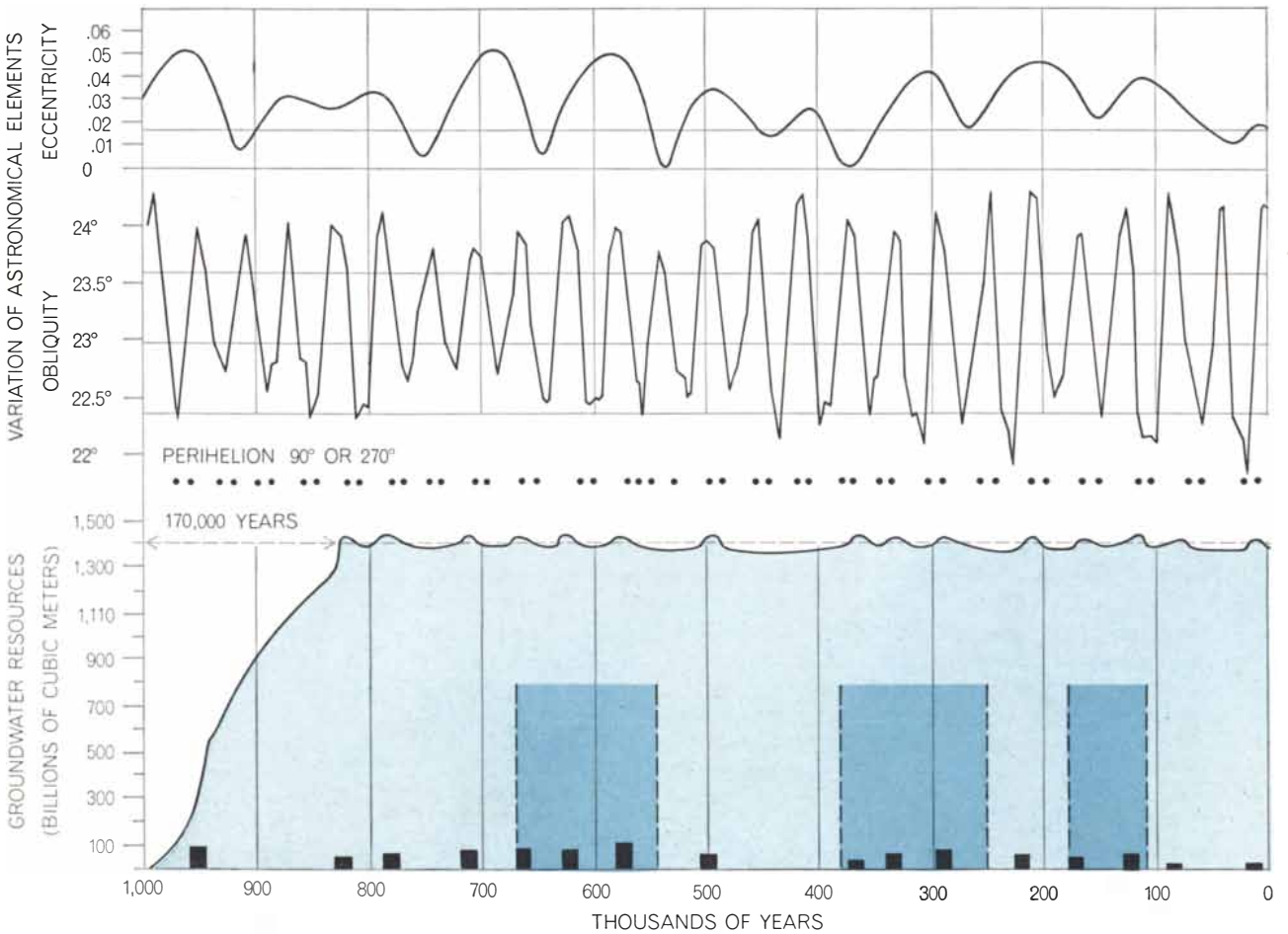
Related to the problem of improving irrigation practices is the problem of controlling the salinity of the soil in oases. Even fresh groundwater contains some salt: a well yielding 20 liters of water per second can produce more than 600 metric tons of salt a year. About half of the salt is retained in the soil, with the other parts assimilated by plants or returning to the water table. Moreover, evaporation of water near the surface increases the concentration of salt.

Under such circumstances a cycle that is difficult to break often materializes at an oasis. An oasis has a shallow water table in which the salt concentration increases both from evaporation and from recharging with excess water from irrigation. The water table is also recharged steadily by the extensive canal system of the oasis and sometimes by losses from artesian wells. Hence the table rises repeatedly to or near the surface in the lower areas. In such waterlogged conditions evaporation is at its most efficient level, so that the concentration of salt in the water and soil increases. To wash the saline soil more irrigation water is needed from deep artesian wells, and so the cycle is renewed. The curbing of salinity requires control of the water-table level, maintenance of a system of drainage, and control of the flow of artesian wells—in short, sound irrigation practices.

Still another problem that policies for Saharan development should take into account is the fact that the recharge and discharge of groundwater are usually in rather delicate balance under desert conditions. The generally low rate of recharge may easily be overtaxed by concentrated withdrawals. When that happens, the groundwater is

| PRINCIPAL GROUNDWATER BASINS OF THE SAHARA | BASIN AREA SQUARE KILOMETERS (THOUSANDS) | WATER-STORAGE CAPACITY CUBIC METERS (MILLIONS) | NATURAL RECHARGE CUBIC METERS (MILLIONS) | ARTESIAN AREA SQUARE KILOMETERS (THOUSANDS) |
|---|---|---|---|---|
| GREAT WESTERN ERG | 330 | 1,500,000 | 400 | 180 |
| GREAT EASTERN ERG | 375 | 1,700,000 | 900 | 325 |
| FEZZAN | 175 | 400,000 | 60 | 25 |
| WESTERN DESERT OF EGYPT | 1,800 | 6,000,000 | 1,500 | 150 |
| CHAD | 1,100 | 3,500,000 | 1,200 | 320 |
| NIGER | 525 | 1,800,000 | 300 | 160 |
| TANEZROUFT | 240 | 400,000 | 20 | |
| | 4,545 | 15,300,000 | 4,380 | 1,160 |

**MAJOR GROUNDWATER BASINS** of the Sahara Desert are alike in many ways but also have some individual characteristics, particularly in the mechanism and volume of recharge: the process by which rainfall percolates directly or indirectly into an aquifer.




**ORBITAL FLUCTUATIONS** of the earth appear to be related to changes in Saharan climate. Etienne A. Bernard of the University of Louvain plotted changes in the eccentricity of the orbit, the obliquity, or tilt, of the earth and the position of perihelion for a million years before the most recent glacial period. Pluvials, or periods of heavy rainfall (*black bars*), were found to coincide with large obliquity and eccentricity and with perihelion at 90 or 270 degrees. The theoretical process by which a major Saharan groundwater basin filled is represented by the curve at bottom. Darker colored spaces between broken lines are interglacial periods, when glaciation in latitudes near the poles was reduced. Often in such periods the water in an aquifer was outcropping, or rising above ground surface.

being mined. The mining of groundwater is understandably a controversial issue in the Sahara.

This concern accounts for the widespread belief in the Sahara that it is important to keep artesian pressure at a level high enough to ensure that the water will flow at ground level without pumping. The chief arguments are that sources of energy are too scarce in the Sahara to justify a resort to unnecessary pumping and that artesian pressure represents a natural balance between recharge and discharge. According to this line of reasoning, an excessive decrease of pressure means overexploitation and mining of groundwater, the Sahara's only water resource.

A more recent view, which I emphatically share, is that it would be better to use up the artesian pressure in a borehole quickly and then draw the water by pumping. The great virtue of this technique is that it would eliminate the losses now occurring from evaporation and from natural discharge. In effect the technique puts a spigot on the well, so that withdrawals occur on a fully controllable basis. The case for this approach has been appreciably strengthened by the recent discovery of oil in the Sahara, which means that the desert has an abundant source of energy for pumping.

Let us assume a situation in which the water in an aquifer that is artesian up to 10 meters above ground level (meaning that the pressure is sufficient to make the water rise that high) is deliberately lowered to an economical pumping depth of 40 meters below-ground—a total drop of 50 meters. Evaporation alone might account for a drop of as much as 30 meters if the artesian pressure were not decreased purposely. The remaining 20 meters would represent a mining of the reserves, provided that no natural discharge existed to draw the level down.

Here, however, another consideration comes into play. Water under artesian conditions emerges from aquifers at a far more rapid rate than water under water-table conditions, since the artesian pressure helps to expel the water. Hence obtaining a given amount of water under water-table conditions represents appreciably less drop in the water level than obtaining it under artesian conditions.

Plainly, then, deliberate replacement of artesian flow by pumping can increase the amount of water available for use. To the extent that the aquifers are actually mined the underground flow of the waters from below the vast regions of the desert that will remain desert can be counted on to maintain the supply of water at favorable pumping sites. This result will come about only if each operation is wisely managed and coordinated with a comprehensive plan for each aquifer based on thorough mapping of its structure. The United Arab Republic is willing to test this technique in the New Valley of the Western Desert and has asked the UN Development Program for financial aid and the Food and Agriculture Organization for technical assistance.

Groundwater is the key to any development effort in the Sahara. If development is to be planned and executed soundly, it should be preceded by a survey of groundwater resources on a Sahara-wide scale. Such a survey would take into account the geographical distribution of the water and the need for equitable treatment of its users regardless of political boundaries.

Several elements would be needed in such a survey. Data must be collected from the various nations that include parts of the Sahara within their boundaries. In addition to a survey of the groundwater resources, there would have to be findings about the water requirements, desirable development plans, the technology of extraction and the organizations that would be needed to carry out the plans. Presumably the results of the survey would be published. The report would constitute the first official assessment of the entire groundwater situation in the Sahara. (This article, indeed, is the first attempt of any kind at such an assessment.)

Some difficulties stand in the way of achieving these objectives. For one thing, investigations of groundwater resources are expensive, particularly in the Sahara. Moreover, most of the nations involved are facing economic difficulties, and their priorities of development are still focused on areas far from their Sahara regions.

These difficulties point to the wisdom of a survey carried out by an international committee representing the local nations, under the sponsorship and technical and financial assistance of the UN and perhaps a group of other nations. The UN and some of its affiliated agencies are already trying to deal with the more urgent problems in Chad, Nigeria, Niger, the United Arab Republic and the Sudan. This activity is needed and helpful, but it is still a piecemeal approach to the problem of the Sahara. That problem must be dealt with on the natural scale of the Sahara and on an international basis that would use modern concepts of development to make the desert's groundwater a resource benefiting all the nations involved.

**NEW VALLEY PROJECT in the United Arab Republic has used groundwater to make sections of the desert produce crops. This potato crop was grown on land thus reclaimed.**

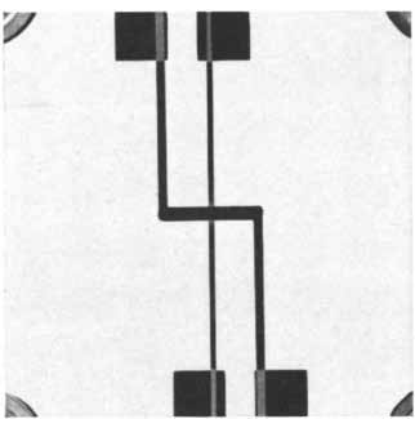
# THE JOSEPHSON EFFECTS

## Predicted in 1962 by a British graduate student, these two unusual manifestations of the superconducting state have now been observed directly. Their theoretical and technological significance is discussed

by Donald N. Langenberg, Douglas J. Scalapino and Barry N. Taylor

Four years ago Brian D. Josephson, a young graduate student in physics at the University of Cambridge, made a startling prediction. On the basis of a purely theoretical analysis of the phenomenon of superconductivity (the abrupt disappearance of electrical resistance in certain substances at temperatures near absolute zero) Josephson came to the conclusion that in principle a "supercurrent" consisting of correlated pairs of electrons could be made to flow across an insulating gap between two superconducting bodies, provided that the gap was small enough. He further suggested that this "tunneling" of electron pairs through an insulator could take two forms, which have come to be known as the Josephson effects. Both forms have been observed in recent experiments.

The nature of the Josephson effects can be understood in a general way by considering what happens when an electric current flows in a superconductor [*see illustration on page 32*]. If a direct current is made to flow in a bar consisting of a superconducting substance, a voltmeter connected across the ends of the bar will indicate that the drop in voltage across the bar is zero; thus the bar has no resistance and is said to be in the superconducting state. If the bar is now divided in two and the pieces are separated by a distance of, say, a centimeter, no current will flow in the opened circuit, and the voltmeter will indicate a voltage equal to the open-circuit voltage of the current source (for example a battery).



**JOSEPHSON JUNCTION consists of two superconducting tin strips separated by an insulating layer of tin oxide 10 angstroms thick. The glass slide on which the junction is mounted is about an inch square. The procedure for fabricating such junctions is shown in the bottom illustration on page 34.**

If the distance between the two pieces is reduced to about 10 angstrom units, however, one of two surprising things can happen. The first is that the voltmeter shows no voltage between the two pieces of superconductor, but a direct current is observed to flow in the circuit even though the two pieces are still physically separated. In other words, the current can flow without resistance not only through the two pieces of superconductor but also across the gap between them. This phenomenon is called the d.c. Josephson effect.

The second thing that can happen is that a direct current flows in the circuit, but the voltmeter indicates a voltage. Simultaneously very high-frequency electromagnetic radiation emanates from the gap, indicating the presence in the gap of a very high-frequency alternating current. This phenomenon is called the a.c. Josephson effect. Like the d.c. effect, the a.c. effect is a direct consequence of the unique nature of the superconducting state.

The investigation of the two effects has already made important contributions to our understanding of superconductivity, and it now appears that they may also have useful applications in technology. Such applications include devices for generating extremely short-wavelength electromagnetic radiation, for measuring very small magnetic fields and for providing highly precise voltage references. Perhaps more important, the Josephson effects may enable physicists to gain an even deeper understanding of superconductivity and to measure some of the fundamental constants of physics with an accuracy never before achieved. Before discussing in detail these somewhat exotic phenomena and their connection with superconductivity, we should like to review some of the salient features of the superconducting state.

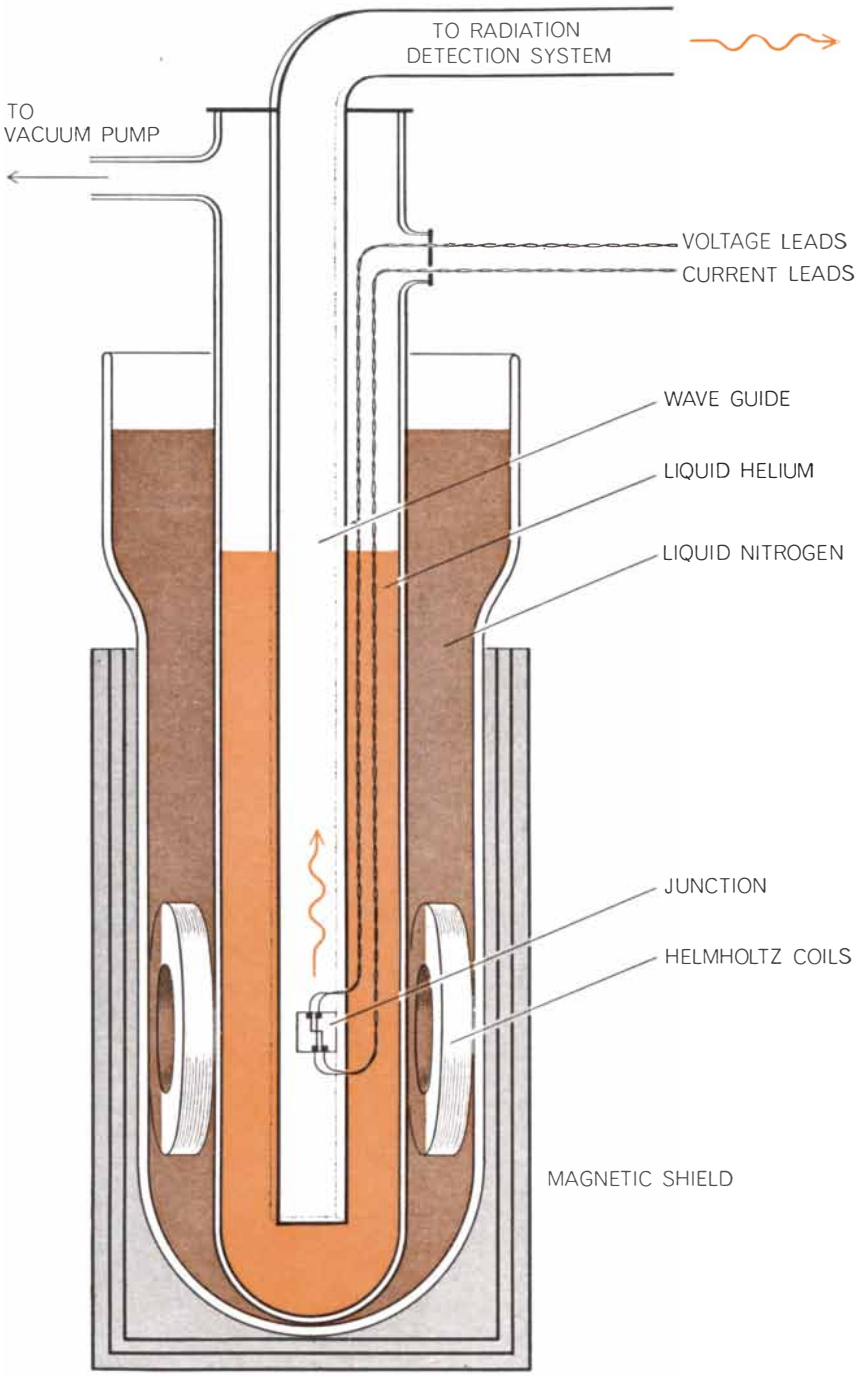
The phenomenon of superconductivity was discovered in 1911 by Heike Kamerlingh Onnes of the Netherlands. He observed that in a sample of mercury all resistance to the flow of electric current vanished when the sample was cooled below a characteristic temperature (now called the superconducting transition temperature). Since 1911 the number of known superconductors has grown to several hundred and includes a number of metallic elements, many metallic alloys and even a few semiconductors. The transition temperatures of all the known superconductors lie below 20 degrees Kelvin (degrees centigrade above absolute zero), and in most cases the transition temperatures are below 5 degrees K., a temperature region that is accessible only by using liquid helium as a refrigerant or by resorting to more sophisticated techniques. The experimental study of superconductivity therefore lies in the realm of low-temperature physics.

For several decades after Onnes' discovery it was believed that a metal in

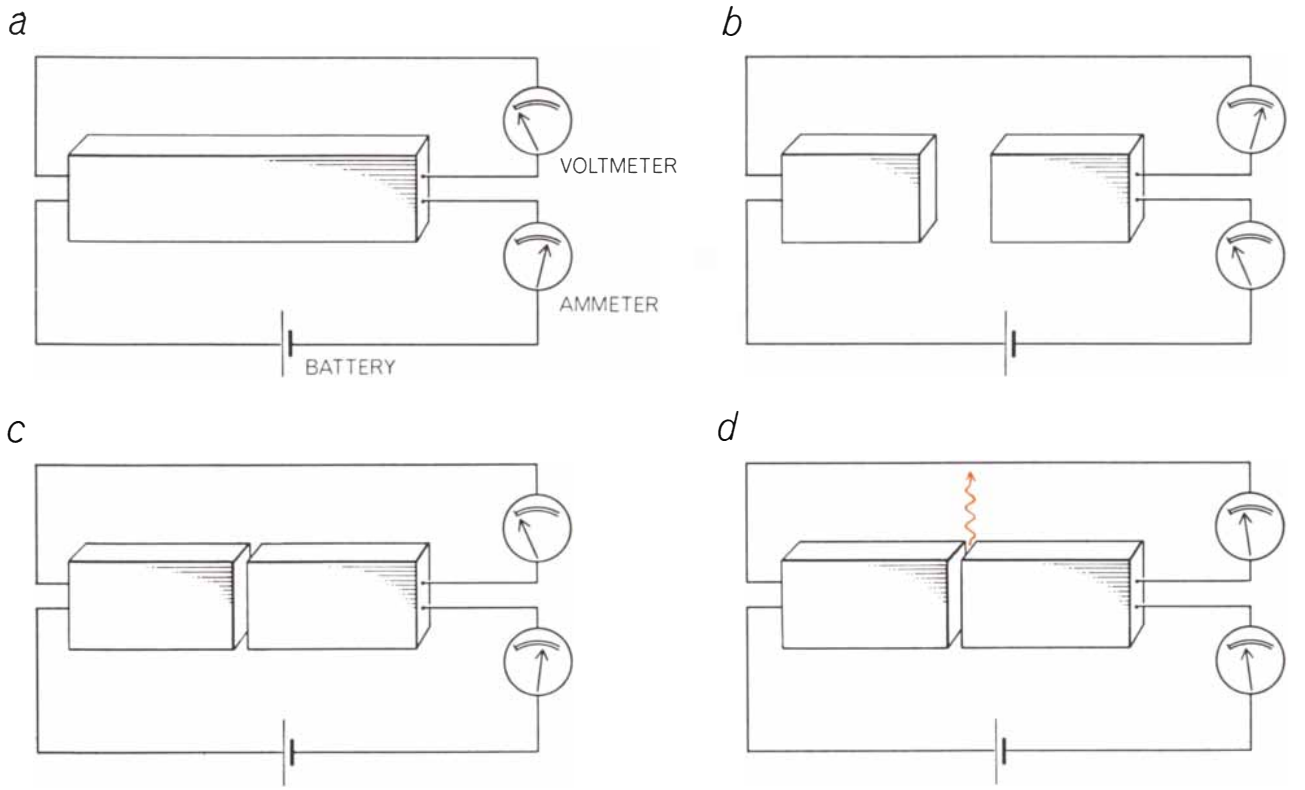
the superconducting state could be characterized simply as a metal with zero electrical resistance or infinite electrical conductivity. Then in 1933 the German investigators W. Meissner and R. Ochsenfeld discovered that there is more to it than that. They found that an externally applied magnetic field is excluded from a superconductor either when it is cooled below its transition temperature in the presence of the field or when the field is applied after the substance has become superconducting. A substance with infinite conductivity would exhibit the latter behavior but not the former; it would tend to "freeze in" any field present when it became superconducting, not expel it. This effect, now called the Meissner effect, is therefore not a consequence of infinite conductivity but a distinct and perhaps more fundamental property of the superconducting state.

The existence of the Meissner effect and certain other properties of superconductors led the theoretical physicist Fritz London to a highly significant insight into the nature of superconductivity. He suggested in 1935 that the superconducting state is a manifestation of quantum mechanics operating on a macroscopic scale—a state with long-range order, in which the motions of a significant fraction of the electrons throughout the entire bulk of the superconductor are correlated. Thus a piece of metal in the superconducting state is in some respects like a single giant molecule. This idea led to a qualitative understanding of many of the unique properties of superconductors. It suggested, for example, an explanation for the characteristic infinite conductivity. A normal metal exhibits resistance to the flow of electric current because any concerted motion of the electrons in one direction is dissipated rapidly by the scattering of individual electrons from the vibrating atoms of the metal or from impurities or imperfections in its structure. If the electrons are in a state in which the motion of each electron is correlated with the motions of all the other electrons, however, and if this correlation extends throughout the metal, the scattering of one electron will necessarily involve all the others. This "united we stand, divided we fall" property makes the scattering of electrons impossible or at least highly improbable, and a supercurrent flow, once started, is immune to the scattering that retards normal currents.

Although London's idea provided physicists with a new and fruitful viewpoint on superconductivity, the microscopic origin and nature of the superconducting state was not really understood until 1957, when John Bardeen, L. N. Cooper and J. R. Schrieffer, then at the University of Illinois, published a now famous theoretical paper on superconductivity. According to their theory, superconductivity occurs because of the existence of an attractive force between the electrons in a metal. Although electrons, each having a negative charge, repel each other in free space, this need not be the case in a metal. There a negatively charged elec-




**EXPERIMENTAL SETUP was used by the authors to detect microwave radiation emitted by Josephson junctions. The junctions were mounted inside a wave guide: a rectangular metal tube in which electromagnetic radiation can propagate. Wires were connected to the junction so that a current could be supplied to the junction and the voltage across the junction could be measured. The wave guide and the junction were inserted in a Dewar vessel (a vacuum-insulated container similar to a Thermos bottle) that could be filled with liquid helium for cooling the junction to a temperature one or two degrees above absolute zero. Outside the helium Dewar vessel there was a pair of coils for producing the necessary magnetic fields. The entire arrangement was surrounded by a triple-walled magnetic shield to eliminate the earth's magnetic field inside the Dewar vessel.**




**JOSEPHSON EFFECTS can be understood in a general way by considering what happens when an electric current flows in a superconductor. The absence of resistance in a superconductor is demonstrated by the fact that no voltage drop appears across a superconducting bar when a direct current is made to flow through it (*a*). If the bar is divided in two and the pieces are separated by a distance of, say, a centimeter (*b*), no current will flow in the opened circuit, and the voltmeter will indicate a voltage equal to the open-circuit voltage of the current source (in this case a battery). If the distance between the two pieces is reduced to about 10 angstroms, however, one of two surprising things can happen. The first is that the voltmeter shows no voltage between the two pieces of superconductor but a direct current is observed to flow in the circuit even though the two pieces are still physically separated (*c*). This phenomenon is called the d.c. Josephson effect. The second thing that can happen is that a direct current flows in the circuit but the voltmeter indicates a voltage (*d*). Simultaneously very high-frequency radiation emanates from the gap, indicating the presence in the gap of a very high-frequency alternating current. This phenomenon is called the a.c. Josephson effect.**

tron moving through a lattice of metal ions attracts the positively charged ions. This distorts the lattice, creating a wake of excess positive charge to which another electron can be attracted. Thus in a metal there can be, in addition to the usual repulsive force between electrons, an indirect attractive force that arises from the lattice of metal ions. In order for a metal to be a superconductor this lattice-mediated attractive force must exceed the repulsive force—the net interaction of electrons must be attractive.

The involvement of the lattice in the attractive interaction explains the seemingly peculiar fact that superconductivity has never been observed in the metals that are usually considered to be the best conductors, such as copper and silver, whereas it is a common phenomenon among the poorer conductors, such as lead and tin. The high conductivity of copper and silver is a consequence of the comparatively weak interaction of electrons with the lattice in these metals. This reduces the scattering of single electrons that impairs conductivity in the normal, or nonsuperconducting, state, but it also reduces the attractive interaction of electrons that leads to superconductivity.

The attractive force tends to couple together in "bound pairs" electrons that have equal and opposite momentum and spin. This binding is extremely weak, however, as revealed by the fact that it is disrupted, and superconductivity is destroyed, by thermal disorder at temperatures just a few degrees above absolute zero. Because the attraction is weak the two paired electrons are, on the average, separated by a distance that is thousands of times greater than the distance between the lattice ions. Since there are usually several electrons for each ion, the electrons of each bound pair range over a volume that simultaneously contains millions of other electron pairs. This spatial overlapping of the pairs has important consequences that arise primarily from the principle of quantum mechanics called the exclusion principle, which states that two electrons with the same spin cannot occupy the same spatial position. If the requirements of the exclusion principle are to be met, the motions of all the pairs must be correlated. The Bardeen-Cooper-Schrieffer theory showed that the correlation is accomplished if the centers of mass of all the pairs move with the same momentum. This equality of the center-of-mass momentum of the bound electron pairs throughout the superconductor is the long-range order envisioned by London. All the electron pairs are locked together by the requirement that they have a common center-of-mass momentum. Disturbing one pair disturbs all the pairs, because of the cooperative nature of this momentum-ordering.

In the quantum-mechanical description of this ordering the wave aspects of electrons must be taken into account. An electron pair with a center-of-mass momentum $p$ can be described by a wave with wavelength $h/p$, where $h$ is Planck's constant. In terms of the quantum-mechanical wave picture, equality

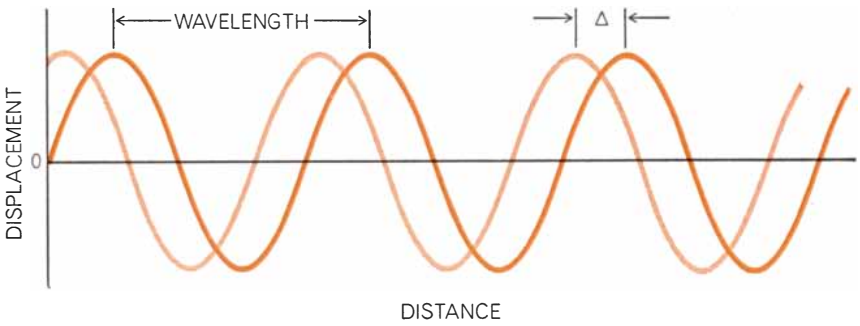
of the center-of-mass momentum of all the pairs means that the waves describing the pairs have the same wavelength. There is more to the superconducting correlations than this, however. The upper illustration on this page shows two waves that have the same wavelength but are not identical. They can be made identical by sliding the light-colored wave forward by a certain distance. The waves are then said to be in phase, or to have the same phase. In a superconductor the waves of all the pairs have not only the same wavelength but also the same phase.

To reiterate, the concept of the phase of an electron pair is a purely quantum-mechanical notion arising from the wave properties of matter. The identity of the pair phases in a superconductor is a quantum-mechanical effect operating on a macroscopic scale. This phase identity is enforced by energy considerations. In order to optimize the average binding energy of the spatially overlapping pairs within the restrictions imposed by the exclusion principle, the phases of all pair waves must be the same. This is the precise quantum-mechanical statement corresponding to the fact that the center-of-mass momentum of all pairs is the same. Because this is the key to understanding the Josephson effects, we must be quite explicit about what we mean by phase.

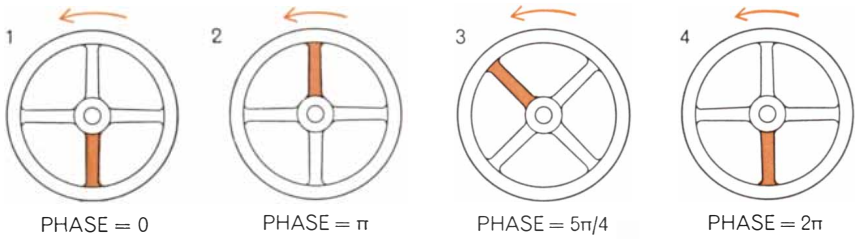
The phase of a periodic motion is a measure of the fractional number of cycles (multiplied by $2\pi$) through which the system has advanced from some arbitrary but fixed reference configuration. An example that may clarify the meaning of phase is a rotating wheel with one colored spoke [*see lower illustration on this page*]. Taking as a reference the position in which the colored spoke is vertically down (*position 1*), the phase is indicated for several different configurations. For example, in position *2* the wheel has turned through half a cycle, and we say the phase has advanced by $\pi$. It is clear, comparing position *1* and position *4*, that the physical configuration of the wheel is the same for a phase equal to zero and a phase equal to $2\pi$. We say that the phase of position *1* and position *4* are the same, with respect to the "modulus" $2\pi$. The motion of the wheel depends on the way the phase develops in time. For example, if the phase of the wheel varies linearly with time, the wheel rotates at constant speed. The time interval during which the wheel completes a cycle and the phase increases by $2\pi$ is called the period of the motion.

In general, a system can be periodic in space as well as in time. An example is the displacement of the surface of a pond when a wave is created by dropping in a pebble. The phase of such a wave depends on both the spatial distance and the time lapse with respect to some reference point in space and time. In the top illustration on the next page the space and time development of a simple sinusoidal wave is shown. The wavelength of the disturbance is the distance over which one spatial oscillation occurs and the phase of the displacement changes by $2\pi$. The period is the time interval over which one temporal oscillation occurs and the phase of the displacement changes by $2\pi$. The phase at several points on the wave is given with respect to the point of origin. The broken line shows the space-time development of a particular point of constant phase, the one corresponding to zero phase. The rate at which this point of constant phase moves in space is called the phase velocity of the wave.

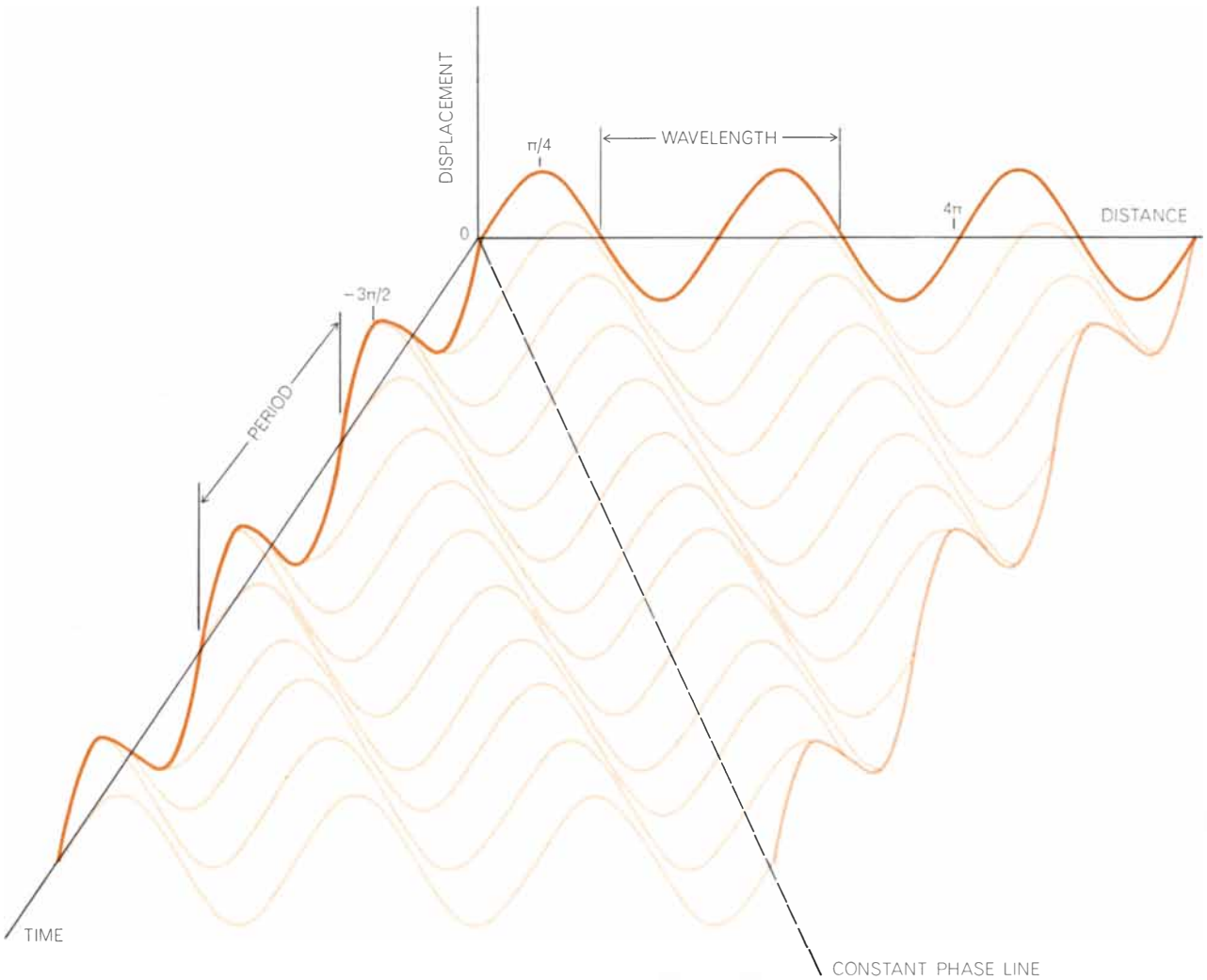
Now, as we have mentioned, according to quantum mechanics the wave associated with an electron pair has a spatial oscillation whose wavelength is determined by the center-of-mass momentum of the pair. The wave also has a time oscillation whose period is determined by the energy of the electron pair, so that the phase of the pair depends on the pair's energy as well as on its center-of-mass momentum. As we have seen, in a bulk superconductor the attractive interaction of electrons, the large number of bound electron pairs and the exclusion principle conspire to make the pair phases the same. These two facts lead to a simple explanation of the zero resistance of the superconducting state: If a voltage difference $V$ existed between the two ends of the current-carrying superconducting bar shown in the illustration on the opposite page, the energy of an electron pair in one end would be greater by $2eV$ than the energy of an electron pair in the other end ($e$ is the charge of an electron). Then, as time passed, a phase difference would develop between the electron pairs in the two ends of the bar. Rather than go to the higher energy state that this breakdown of the pair phase-locking would produce, the superconductor carries the current with-



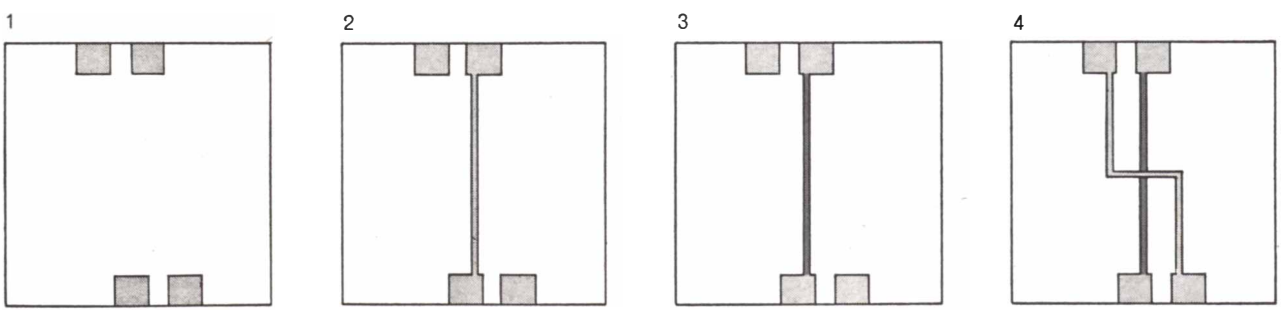

**TWO WAVES can have the same wavelength but different phases. They can be made identical by sliding the light-colored wave forward by the distance Δ. The waves are then said to be in phase, or to have the same phase. In a superconductor the waves of all the electron pairs have not only the same wavelength but also the same phase.**




**ROTATING WHEEL can be used to clarify the meaning of phase. The phase of the wheel's motion is a measure of the fractional number of cycles (multiplied by $2\pi$) through which the wheel has advanced from some arbitrary but fixed reference configuration. Taking as a reference the position in which the colored spoke is vertically down (*position 1*), the phase is given for three other configurations. The phase of position *1* and position *4* are said to be the same with respect to the "modulus" $2\pi$. The time interval during which the wheel completes a cycle and the phase is increased by $2\pi$ is called the period of the motion.**




**TRAVELING WAVE, that is, one that varies periodically in both space and time, is shown here for a simple sinusoidal disturbance analogous to the ripples produced on the surface of a pond by dropping in a pebble. The wavelength is the distance over which one spatial oscillation occurs. The period is the time interval over which one temporal oscillation occurs. The phase at several points on the wave is given with respect to point of origin (*0*). Broken line shows space-time development of a particular point of constant phase, the one corresponding to zero phase. The rate at which this point moves in space is called the phase velocity of the wave. According to quantum mechanics the wave associated with an electron pair in a superconductor has a spatial oscillation, whose wavelength is determined by the pair's center-of-mass momentum, and a time oscillation, whose period is determined by the pair's energy.**



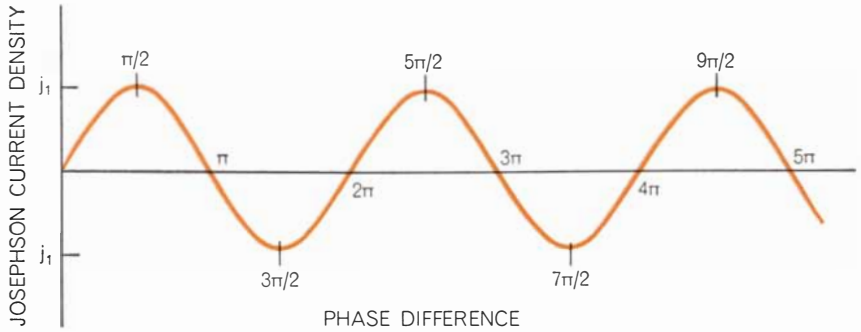

**PROCEDURE for fabricating a Josephson junction begins with the deposition of four electrodes, in the form of thin metal films, on a glass slide (*1*). This is done by heating the metal in a vacuum chamber until some of it evaporates; the resulting metallic vapor is passed through a mask before being deposited on the slide. Next a thin film of a superconducting substance (for example tin) is deposited on the slide in the form of a strip that makes contact with two of the previously deposited electrodes (*2*). The strip is typically one millimeter wide and about 2,000 angstroms thick. The third step is the formation of a very thin layer (about 10 angstroms thick) of insulating oxide on the surface of the bottom strip (*3*). This is accomplished by admitting a carefully controlled amount of air or pure oxygen to the vacuum chamber. The junction is completed by depositing a second strip of superconductor on top of the oxide layer, usually at right angles to the bottom strip (*4*). This strip makes contact with the two remaining electrodes. Wires for supplying a current to the junction and for measuring the voltage drop across the junction are then soldered to the electrodes.**

out allowing a voltage difference to appear.

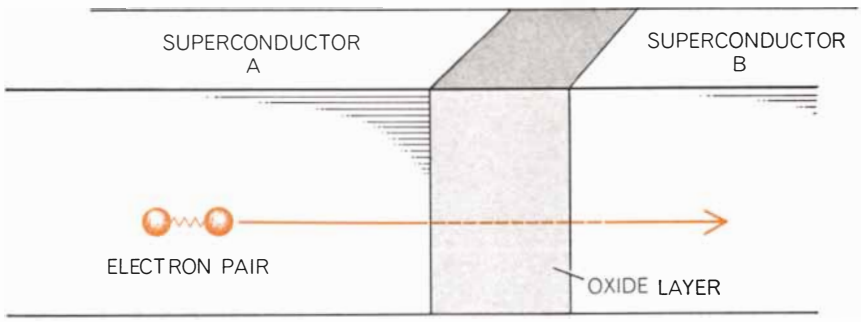
What Josephson did in 1962 was to perceive that it should be possible to modify the phase-locking and hence study in detail this aspect of the superconducting long-range order. He considered the situation shown in the illustration on page 32 and argued as follows: The pair phase must be the same throughout a single piece of superconductor, since pairs can move freely through it. If the superconductor is divided into two pieces and the pieces are well separated so that pairs cannot be exchanged between them, there need be no particular relation between the pair phases of the two pieces. If the two superconductors can be brought close enough together, however, an intermediate situation will result in which there can be some exchange of electron pairs by means of the quantum-mechanical process called tunneling. (Because of their wavelike nature, electrons can tunnel, or penetrate, through barriers they could not penetrate if they were simply particles.) In this case the overall system can assume a state of minimum energy in which there is a unique difference between the pair phases in the two superconductors. It should then be possible to vary this phase difference, or relative phase, by controlling the rate of pair transfer between the two pieces of superconductor.

The intermediate situation can in principle be achieved simply by separating the two pieces by a distance on the order of 10 angstroms. Unfortunately no one actually knows how to construct such an arrangement, but a completely equivalent one can be realized in practice using a procedure developed by Ivar Giaever and John C. Fisher of the General Electric Research Laboratory [*see bottom illustration on opposite page*]. The essential feature of the technique is that the two superconductors are separated by a thin layer of insulating oxide, which is allowed to form on one of them before the other is deposited on top. The result is a metal-insulator-metal sandwich with superconducting bread and insulating salami. Such a structure is called a tunnel junction [*see illustration on page 30*]. The tunneling of pairs between the two superconductors of such a junction leads to a coupling of the pair phases on the two sides, which can be modified by electric and magnetic fields as Josephson envisioned.

Josephson predicted that if somehow a phase difference is produced between

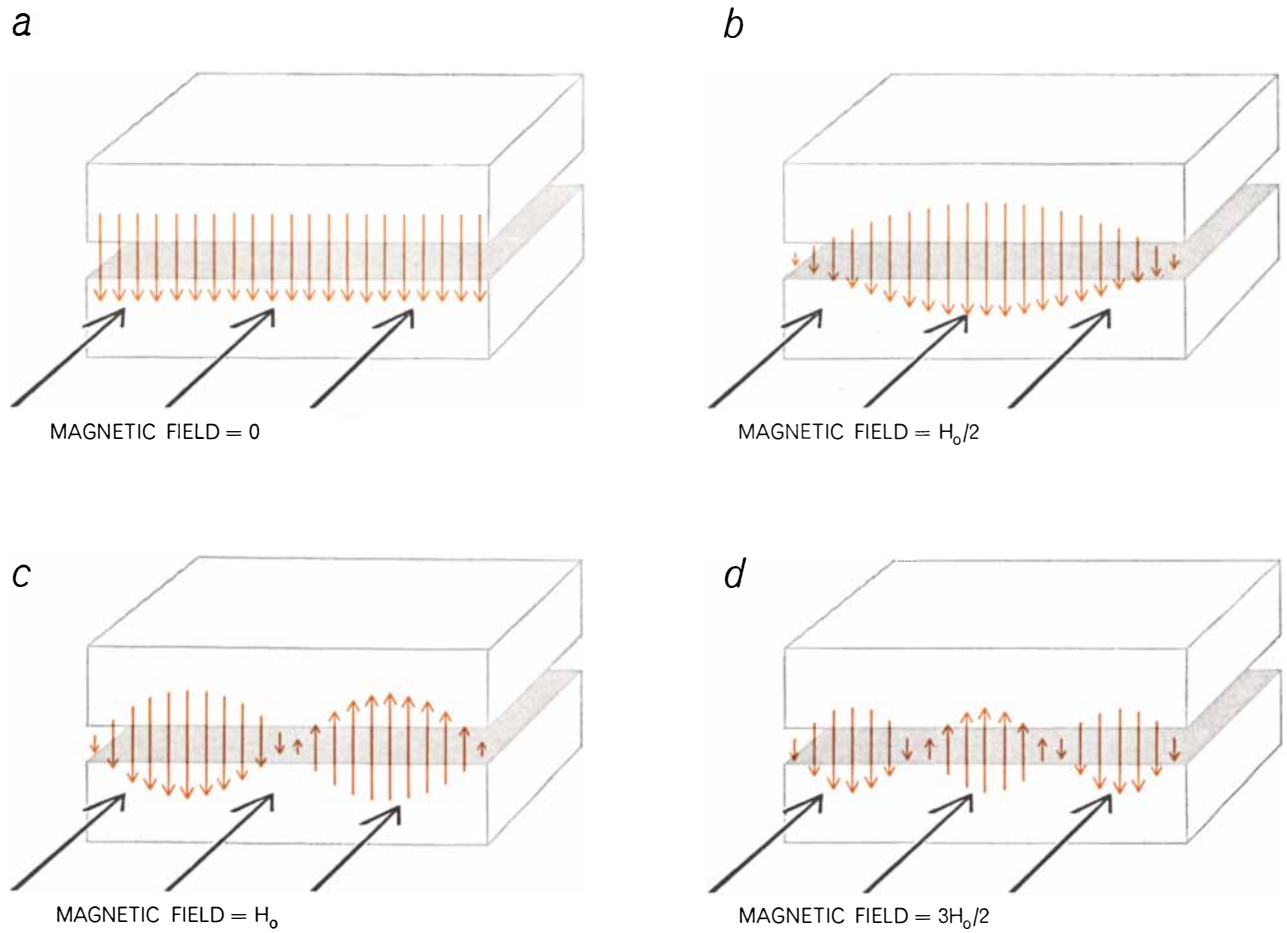



**CURRENT DENSITY, or current per unit area, in a Josephson junction is a sinusoidal function of the difference in the phases of the electron pairs in the two superconductors. Current density has a maximum value of $j_1$ when the phase difference is some odd multiple of $\pi/2$. Current density is zero when the phase difference is an integer multiple of $\pi$.**




| PHASE OF PAIRS IN A | PHASE OF PAIRS IN B | CHANGE IN PHASE THROUGH OXIDE LAYER | PHASE OF PAIR AFTER GOING FROM A TO B | PHASE OF PAIR AFTER GOING FROM B TO A | JOSEPHSON CURRENT (MAXIMUM EQUALS $j_1$) |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | π/4 | π/4 | π/4 | π/2 | $j_1/\sqrt{2}$ |
| 0 | π/2 | π/2 | π/2 | π | $j_1$ |
| 0 | 3π/4 | 3π/4 | 3π/4 | 3π/2 | $j_1\sqrt{2}$ |
| 0 | π | π | π | 2π | 0 |

**PERIODIC RELATION between the junction current density and the pair phase difference can be understood by remembering that the phase of a pair depends on its motion. The schematic diagram at top shows two superconductors, labeled *A* and *B*, separated by an insulating oxide layer. The table at bottom shows how the transfer of electron pairs from *A* to *B* and from *B* to *A* is related to the difference in the pair phases in the two superconductors; it also indicates the net current for this relative pair phase. The pair phase in superconductor *A* is taken to be zero. If the pair phase in superconductor *B* is also zero (*first line in table*), the transfer of pairs in either direction is equally likely and the net junction current will be zero. In the second line of the table the situation for a pair phase of $\pi/4$ in superconductor *B* is shown. The change in phase of a pair that traverses the oxide layer is $\pi/4$. The phase of a pair going from *A* to *B* thus changes from zero to $\pi/4$; when it reaches side *B*, its phase exactly matches the phase on side *B*, it fits in nicely with the other pairs on side *B*, and such a transfer is relatively probable. The phase of a pair going from *B* to *A*, however, changes from $\pi/4$ to $\pi/2$, which does not match well with the zero pair phase of the other pairs on side *A*. The transfer of a pair from *B* to *A* is therefore not as likely to occur as the transfer of a pair from *A* to *B*. On the average there will be a net flow of pairs from *A* to *B* and hence a current. The phase mismatch for pairs going from *B* to *A* in the third line of the table is even worse, and therefore the number of pairs going from *B* to *A* is less. Consequently the net current from *A* to *B* is increased. As the relative pair phase continues to increase in lines four and five, the mismatch is reduced and net current from *A* to *B* decreases again. Table describes first half-cycle of curve at top of page.**




**EFFECT OF A MAGNETIC FIELD** on a direct current passing through a Josephson junction is shown in these schematic diagrams. The external magnetic field (*black arrows*) is applied in the plane of the junction at right angles to one side of the junction. In *a* the magnetic field is zero and the magnitude of the current, as represented by the length of the colored arrows, is the same at all points of the junction. In *b* the applied magnetic field ($H_0/2$) is just strong enough to cause the wavelength of the Josephson current to equal twice the length of the junction; thus half the wavelength fits exactly into the length of the junction. In *c* the magnetic field has been increased to $H_0$, so that a full wavelength fits into the junction. The current now reverses direction once; equal currents flow in both directions and the total junction current is zero. In *d* the field has been increased to $3H_0/2$; three half-wavelengths fit into the junction, the current reverses direction twice and again there is a net current across the junction. The total current is not as large as it was in *a* or *b*. A graph showing how the total junction current depends on the strength of the magnetic field appears on the opposite page.

the two superconductors, pairs will be preferentially transferred in one direction and a current will flow between the two superconductors. (In a real laboratory experiment it is the current that is under the direct control of the experimenter, not the phase difference. The phase difference is produced by causing a current to flow in the junction. It is, however, conceptually simpler to think of the phase difference as the controllable quantity and then to ask what current results.) The junction current density in Josephson's theory is a sinusoidal function of the phase difference [*see top illustration on preceding page*]. This rather strange periodic relation between the current density and the phase can be understood by remembering that the phase of a pair depends on its motion. Pairs transferred in the preferred direction are simply changing their phase by just the amount required to match the pair phase on the side to which they are going. Pairs that attempt to travel in the opposite direction will shift their phase by the same amount. If the resulting phase matches the pair phase on the side to which they are going, they are able to make the transition, the number of pairs traveling in both directions is the same and the net current is zero. If the resulting phase does not match, the pairs will be reflected back to the side from which they came, and the transfer of pairs in the preferred direction will give rise to a current [*see bottom illustration on preceding page*]. There is thus a direct current flow without a voltage drop between the two superconductors; the *entire* junction behaves like a single bar of superconductor. This is the d.c. Josephson effect.

The first indisputable experimental confirmation of the d.c. Josephson effect was reported in 1963 by John Rowell of the Bell Telephone Laboratories. He observed the predicted resistanceless current flow in a junction and studied its dependence on an externally applied magnetic field. Observation of the magnetic-field dependence was essential, because such a resistanceless current could also be due to the presence of small "bridges" of superconductor across the junction. (Indeed, it appears in retrospect that many workers had observed the d.c. Josephson effect but had ascribed the resistanceless currents they observed to such bridges and had done their best to ignore this supposed undesirable "dirt" effect.) A bridge current can be modified only by a rather large magnetic field, but the d.c. Josephson current has

a unique periodic variation in quite small magnetic fields. This variation arises in the following way.

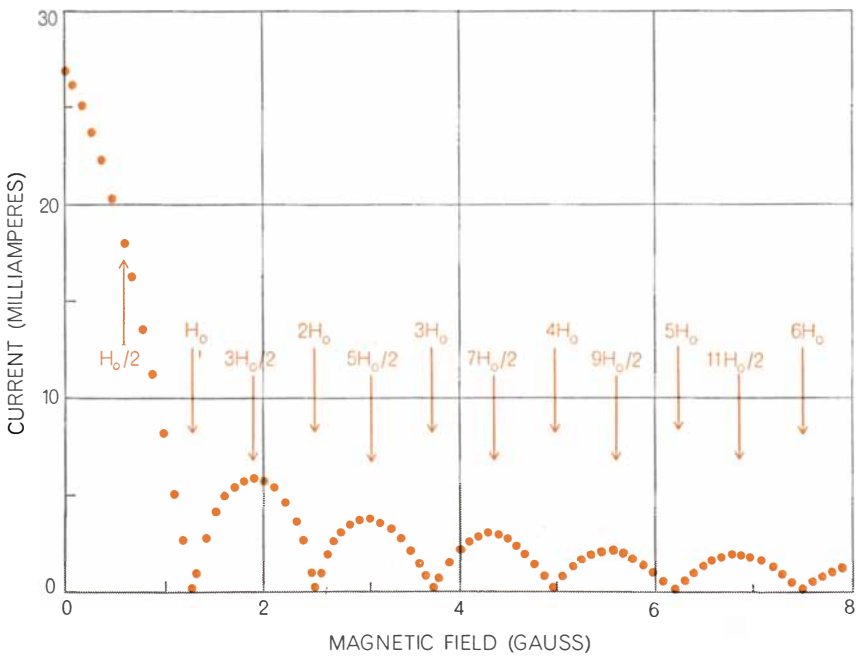
In quantum mechanics the phase of the wave associated with a particle (or a bound electron pair in a superconductor) depends on the magnetic field (more precisely, on something called the magnetic vector potential). It turns out that if there is a magnetic field in a tunnel junction, the difference between the pair phases in the two superconductors has a spatial variation. If the field happens to be uniform and constant throughout the junction oxide layer, the phase varies in the plane of the junction in a direction at right angles to the direction of the field and at a rate proportional to the magnitude of the field. Because of the periodic dependence of the current density on the phase, the direct current in the junction oscillates in space and may reverse its direction at several points in the junction if the magnetic field is large enough. The maximum net resistanceless direct current that can be carried by the junction therefore varies periodically as the magnetic field is increased [*see illustration on this page*]. Rowell's observation of precisely this behavior clinched the identification of the observed resistanceless current as the d.c. Josephson effect.

So far we have considered only situations where the pair phase difference between the two superconductors of the junction does not vary in time. We have seen, however, that if there is a voltage difference and hence a potential-energy difference between the two superconductors, the phase difference *will* vary in time. The time-independent phase difference that exists when a direct current flows in the junction is in fact initially produced by a momentary voltage difference across the junction that occurs when an external current source is connected to it. The voltage drop causes the phase to shift in time. When the phase difference attains the value that corresponds to the current determined by the current source, the voltage drop vanishes, and the relative pair phase thereafter remains constant in time. This happens in about a ten-billionth of a second. If the current source forces the current to exceed the maximum d.c. Josephson current, however, a voltage appears across the junction, and the relative phase increases steadily in time. Because of the sinusoidal dependence of the Josephson current on the phase, the current oscillates back and forth between the two superconductors at a frequency proportional to the voltage across the junction. This is the a.c. Josephson effect.

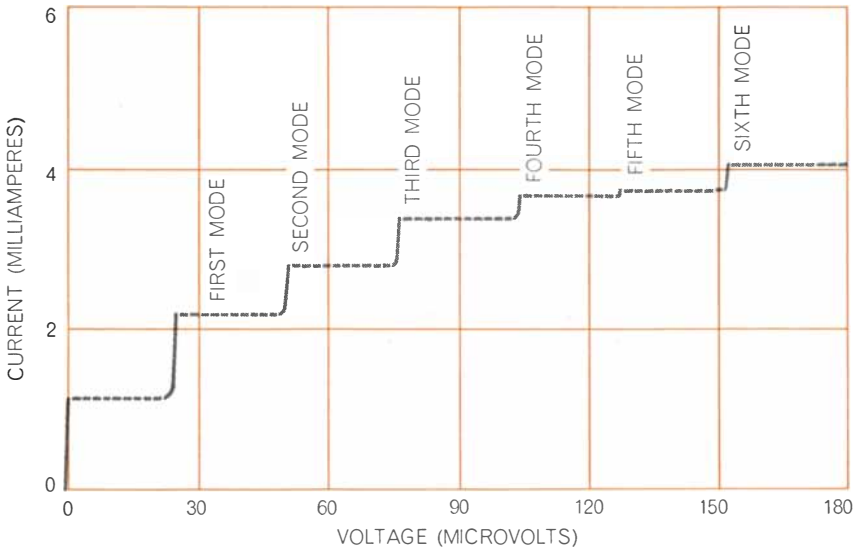
Experimental confirmation of the a.c. Josephson effect has proved to be considerably more difficult than confirmation of the d.c. effect. The relation between the time dependence of the phase and the voltage across the junction is such that if the voltage has a constant value $V$, the frequency $\nu$ of the oscillating supercurrent is $2e/h$ times the voltage, where $e$ is the charge of an electron and $h$ is Planck's constant (thus $\nu = 2eV/h$). The ratio $2e/h$ is numerically equal to 483.6 megacycles per microvolt, and since typical junction voltages range from a few microvolts to several millivolts the frequency of the oscillating supercurrent can be as high as several hundred billion cycles per second. The obvious straightforward way to observe such high-frequency currents is to detect the electromagnetic waves radiated by the current. (In general any oscillating current will radiate electromagnetic waves.) At the frequencies involved the radiation is in the microwave and far-infrared regions of the electromagnetic spectrum. The amount of energy the a.c. Josephson currents radiate, however, is very small and thus rather difficult to detect. Consequently direct experimental confirmation of the a.c. Josephson effect came only after several indirect experiments had left little doubt that the effect really existed.

The first of these indirect confirmations was achieved in 1963 by S. Shapiro, then working for Arthur D. Little, Inc. Shapiro varied the voltage across the junction and measured the current through the junction while it was exposed to microwave radiation supplied by a conventional microwave oscillator. He found abrupt increases in the junction current at certain voltages. When these voltages were substituted into the Josephson frequency-voltage equation, $\nu = 2eV/h$, the frequencies turned out to be whole-number multiples of the frequency of the applied microwave radiation.

This effect can be explained as follows: In addition to a d.c. voltage across the junction, there is also a small voltage induced by the applied microwave radiation that oscillates at the frequency of this radiation. Since the frequency of the Josephson supercurrent depends on the junction voltage, the supercurrent frequency has a small periodic variation in time; in other words, the supercurrent is frequency-modulated. Because of this it contains components that have many frequencies. These frequencies are the algebraic sums of the frequency of the applied microwave radiation plus (or minus) the frequency




**MAXIMUM NET DIRECT CURRENT that can be carried by a Josephson junction varies periodically as the magnetic field is increased. The values of the magnetic fields shown in the diagrams on the opposite page appear in the graph. The observation of precisely this behavior in 1963 by John Rowell of the Bell Telephone Laboratories clinched the identification of the observed resistanceless current in the junction as the d.c. Josephson effect.**




**"STEPS," or abrupt increases, in junction current were observed in the curves that related the current to the voltage of Josephson junctions, even in the absence of externally applied microwave radiation. This observation was an indirect confirmation of the existence of the a.c. Josephson effect. Each step corresponds to a "resonant mode" of the oscillating electromagnetic field that is present between the two superconducting strips in the junction.**

of the Josephson supercurrent plus (or minus) all the harmonic frequencies associated with these two fundamental frequencies. At d.c. voltages for which the Josephson frequency is equal to the microwave frequency or some whole-number multiple of it, among all the possible net frequencies there is one that is equal to zero. This means that there is a zero frequency or direct current at those values of d.c. junction voltage for which this special relation between Josephson frequency and microwave frequency occurs. All of this depends, of course, on the existence of the oscillating Josephson supercurrent in the first place, so that Shapiro's observation represents an indirect confirmation of its existence.

Another indirect confirmation was provided by two of us (Scalapino and Taylor) and R. E. Eck at the University of Pennsylvania. It was observed that "steps," or abrupt increases, in junction current similar to those found by Shapiro appeared in the curves that related the current to the voltage of Josephson junctions, even in the absence of any externally applied microwave radiation [*see illustration above*]. To understand the origin of these steps it is useful to recall that associated with any structure of finite size in which waves can propagate there is a discrete set of "resonant modes," each one corresponding to a particular relation between the wavelength or frequency of the wave and the dimensions of the structure. For example, if a hollow tube in which sound waves can propagate is closed at one end and left open at the other, one has an organ pipe with a set of resonant modes corresponding to a fundamental resonant frequency and a whole series of overtones, or harmonic resonant frequencies. If the pipe is excited by some source of sound at a frequency equal to the fundamental or one of the overtones, an intense standing sound wave is set up in the pipe: the pipe resonates. If it is excited at some frequency other than the fundamental frequency or one of the overtone frequencies, the response is not nearly so great.

Now, a Josephson junction is essentially an electromagnetic organ pipe. Electromagnetic waves can propagate between the two superconductors, and consequently a junction will have a set of resonant electromagnetic modes. A relatively intense electromagnetic field can be excited in the junction if the frequency and wavelength of the exciting source are adjusted so that they match the frequency and wavelength of one of these resonant modes. The origin of the steps observed by Eck, Scalapino and Taylor is now clear. The Josephson supercurrent can be made to vary periodically in space with a wavelength determined by an applied magnetic field, and periodically in time with a frequency determined by the voltage across the junction. When the frequency and wavelength of the supercurrent are thus matched to the frequency and wavelength of one of the junction modes, a large electromagnetic field will be generated in the junction. This field can then react on the Josephson current in the same manner as Shapiro's applied microwave radiation to produce the observed steps in the current-voltage curve.

This discovery was important for two reasons. It provided additional indirect evidence for the existence of the a.c. Josephson effect, and it also provided a key to understanding how the a.c. supercurrent could be made to generate enough electromagnetic radiation in the junction to make possible direct external detection of the radiation. Armed with this knowledge, we embarked on an effort to achieve direct detection of radiation emitted by Josephson junctions. We have recently succeeded in doing so. The results of these experiments confirm in a very direct fashion the existence of the a.c. Josephson effect in superconductors and, perhaps more important, provide us with a powerful new tool for studying the effect.

In our experiments we chose to work at a frequency of about 10 billion cycles per second, because it is a commonly used microwave frequency and equipment and techniques for it are readily available and well known. The voltage corresponding to this frequency is about 20 microvolts. We therefore prepared junctions with the proper lengths so that the first or second resonant mode (or step in the current-voltage curve) occurred at 20 microvolts. These junctions were mounted inside a wave guide—a rectangular metal tube in which electromagnetic radiation can propagate. Wires were connected to the junction so that a d.c. voltage could be applied and the d.c. junction current could be measured. The wave guide and junction were inserted in a Dewar vessel (a vacuum-insulated container similar to a Thermos bottle) that could be filled with liquid helium for cooling the junction to a temperature one or two degrees above absolute zero. Outside the Dewar vessel there was a pair of coils for producing the necessary magnetic fields. The entire arrangement was surrounded by a magnetic shield to eliminate the earth's magnetic field inside the Dewar vessel [*see illustration on page 31*].

Radiation emitted by the junction traveled inside the wave guide up out of the Dewar vessel and into an electronic system that was designed to detect very small amounts of power. In one version this system could detect

as little as $10^{-16}$ watt, about the amount of power in visible light received by a human eye from a 100-watt light bulb 300 miles away. Such high sensitivity was necessary because, although we knew how to make the Josephson supercurrent generate radiation inside the junction, we had not completely solved the problem of getting the radiation out of the junction and into the wave guide. Radiation propagating in the junction is almost entirely reflected back into the junction when it reaches the ends, and very little (only about one part in 100,000) is radiated out into the wave guide.

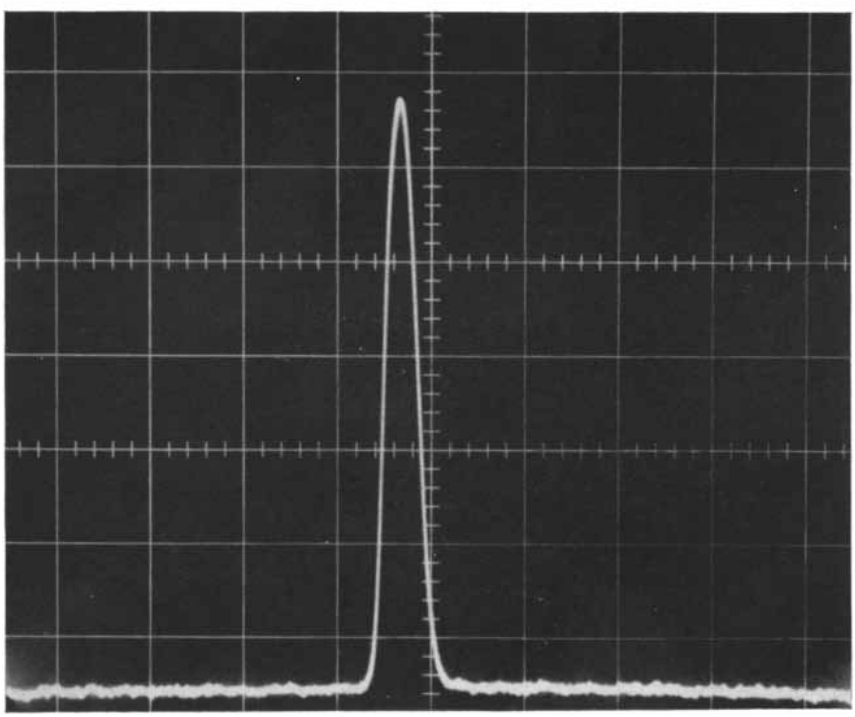
This problem of optimizing the transfer of power from a source (the junction) to a load (the wave guide and the detection system) is an impedance-matching problem analogous to the problem of efficiently transferring power from a high-impedance high-fidelity amplifier to a low-impedance loudspeaker or from a low-impedance man to a high-impedance boulder. The solutions in these examples are impedance-matching devices: an electrical transformer in the first case and a lever or a block and tackle in the second. The solution for the Josephson junction is not so obvious, and we elected to sidestep this difficulty for the moment simply by using a detection system with a sensitivity adequate for detecting the power that *was* radiated. We estimated we might get perhaps a trillionth ($10^{-12}$) of a watt; the available sensitivity of $10^{-16}$ watt provided some insurance.

Once radiation was detected we were able to improve the power transfer somewhat and succeeded in observing up to $10^{-11}$ watt. A typical signal curve appears in the illustration at the right. As predicted by Josephson, the radiation was found to be coherent (all in phase) and at least as monochromatic as the radiation emitted by a conventional vacuum-tube klystron oscillator. The ratio of the frequency of the radiation to the d.c. junction voltage was found to be equal to the predicted value of $2e/h$ to an accuracy of better than 1 percent. Experiments that turn out exactly as expected are rare, however, and this one was no exception. Along with these comforting agreements between theory and experiment there appeared some surprises and some new puzzles, which we are currently studying. Other workers are also active in the field. A group at the Ukrainian Academy of Sciences was the first to report a direct observation of radiation from a Josephson junction; they reported an observation of $10^{-13}$ watt of radiated power, and they are also carrying on a further study of the Josephson radiation.

The direct detection of the a.c. Josephson radiation has opened up the possibility of several rather diverse applications. It provides a sensitive and direct tool for further study of the Josephson effects and superconductivity. For example, simultaneous measurements of the d.c. junction voltage and the frequency of the emitted radiation can yield a highly accurate check on the validity of the Josephson frequency-voltage relation. This is of considerable importance because the frequency-voltage relation is directly connected with some of the most fundamental features of the present theory of superconductivity. If the relation holds up under such careful scrutiny, the fundamental physical constant ratio $e/h$ that appears in it can be determined with an accuracy several times greater than has heretofore been achieved. Here is a unique opportunity to use a macroscopic quantum phenomenon to determine one of the fundamental constants of nature. Experiments along these lines are now in progress in our laboratory.

There are also possible applications in technology. The region of the electromagnetic spectrum between microwaves, with wavelengths measured in centimeters, and infrared waves, with wavelengths measured in thousandths of centimeters, is still relatively unexplored. It has been hard for physicists to perform experiments using radiation in this part of the spectrum because the generation and detection of such radiation has been difficult and expensive. The Josephson junction has promise as a simple and inexpensive source of small amounts of coherent and monochromatic radiation with wavelengths ranging from several millimeters down to a fraction of a millimeter. It would be particularly useful in low-temperature experiments where liquid-helium cooling is already an essential part of the experiment. It will be necessary to solve the power transfer problem in order to obtain the desired powers, but there appear to be no obstacles in principle to doing this.

It has been only four years since Josephson discerned in the theory of superconductivity the effects that now bear his name. During those years the effects have received abundant experimental confirmation and have provided striking direct evidence of the wondrous workings of quantum mechanics on a macroscopic scale in superconductors. Our newfound ability to control the phase of superconducting pairs promises new advances in our understanding of superconductivity as well as benefits in other areas of physics and technology.



**OUTPUT SIGNAL produced by the detection system associated with the authors' experiment appears on the face of an oscilloscope tube. The signal was produced by an input signal of a hundred-billionth of a watt of microwave radiation from a Josephson junction.**

# CHELATION IN MEDICINE

Chelates are molecules that can seize a metal ion in a clawlike structure. Some of these substances are already used in medicine, and the principle seems to have even wider clinical applications

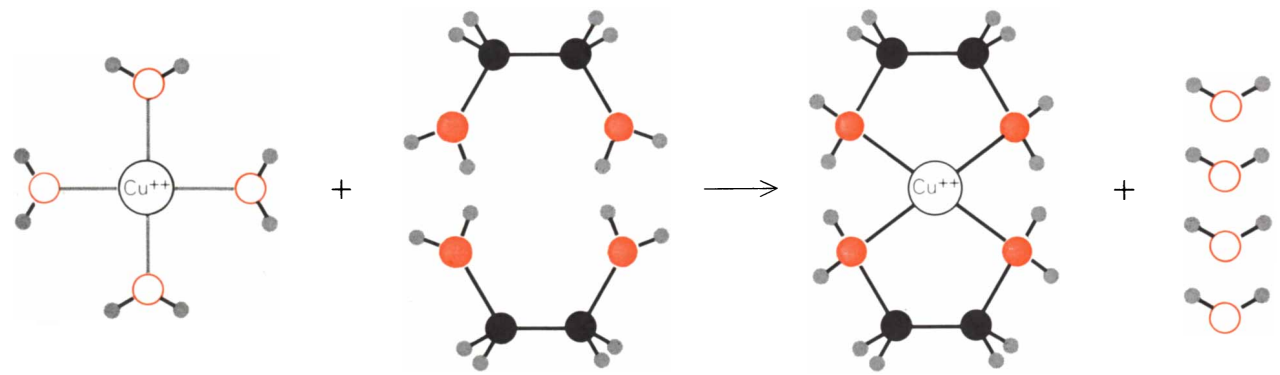
by Jack Schubert

Finding new drugs for the treatment of human diseases is still largely fortuitous. Most of the drugs in current use were discovered by accident or by trial and error, and the cases in which a clear connection has been found between a drug's action in the body and its chemical and physical properties are few. One class of drugs for which such a connection has been established, however, is the group known as the chelating agents. These substances are characterized by their ability to seize and "sequester" metal atoms. Since their various actions as drugs are apparently based at least in part on this property, it offers a promising foundation for the development of a rational pharmacology. The promise is being vigorously explored in laboratories all over the world.

Chelation is a common chemical phenomenon and is associated with many familiar substances. Among the well-known natural chelates are hemoglobin (containing iron), chlorophyll (containing magnesium), vitamin B-12 (containing cobalt) and the enzyme cytochrome oxidase (containing both iron and copper). Among the common substances that can act as chelating agents are citric acid, aspirin, adrenalin, cortisone, Terramycin and a host of other compounds, natural and synthetic. The phenomenon of chelation was recognized many years ago and put to use in various applications, although it was then poorly understood. In 1935 a German chemist, F. Munz, patented a compound called ethylenediaminetetraacetic acid (EDTA) that had a remarkable affinity for calcium. It soon found commercial use in the textile industry as an agent for preventing the precipitation of calcium from the water used in the manufacture of fibers. In 1940 the British chemist Sir Rudolph Peters and his associates developed a chelating agent as an antidote to the poison gas Lewisite. The antidote, called BAL (for British Anti-Lewisite), is based on sulfhydryl groups (SH) that chelate and thus inactivate the arsenic of Lewisite.

It was only a little more than a dozen years ago, however, that chemists in general became aware of the fundamental importance of chelation and began to devote intensive study to its possible commercial and medical applications [see "Chelation," by Harold F. Walton; SCIENTIFIC AMERICAN, June, 1953]. The medical potential of chelating agents was demonstrated in 1951 when EDTA saved the life of a child suffering from lead poisoning. Since then the investigation of the medical uses of chelating agents has produced a voluminous literature, and chelate drugs have been developed for the treatment of a wide range of diseases from metal poisoning to cancer.

A chelating agent is a molecule that is capable of seizing and holding a metal ion in a clawlike grip (the term comes from the Greek word *chele,* meaning claw). Like a claw, the clutching structure forms a ring in which the ion is held by a pair of pincers. The pincers consist of "ligand" atoms (usually nitrogen, oxygen or sulfur), each of which donates two electrons to form a "coordinate" bond with the ion. In most cases the metal ion can be grasped



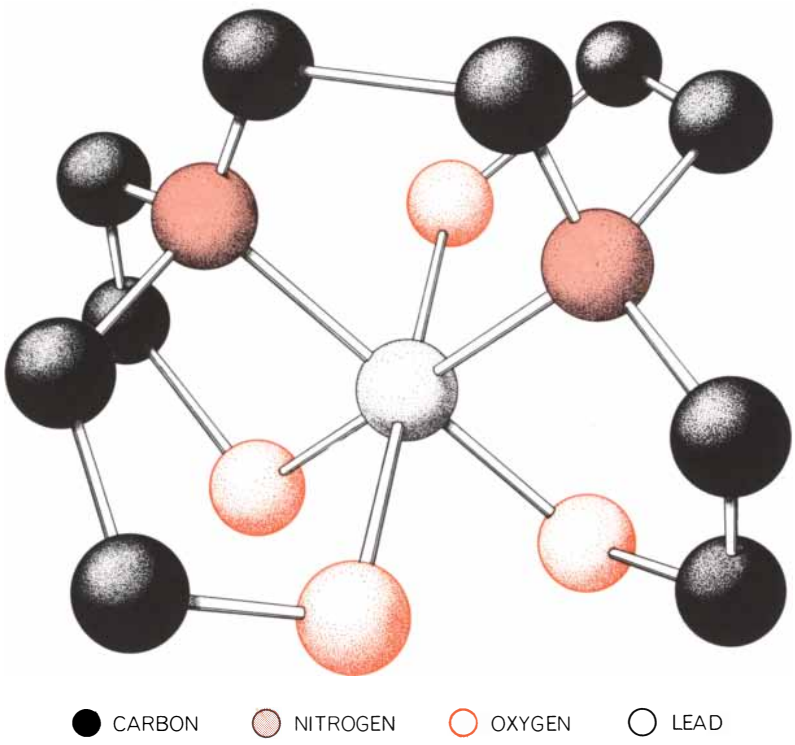

**PRINCIPLE OF CHELATION** is illustrated in the case of an ion of copper in an aqueous solution. The metal ion is in its cupric, or divalent, state ($Cu^{++}$) at left, surrounded by molecules of water. When the latter are displaced by molecules in which nitrogen atoms act as "ligands," the copper ion is sequestered in a ring structure (*right*) and rendered inert.

by more than one molecule, so that the ion is held in a set of rings. Each ring is usually composed of five or six members, the members consisting of single atoms or groups of atoms.

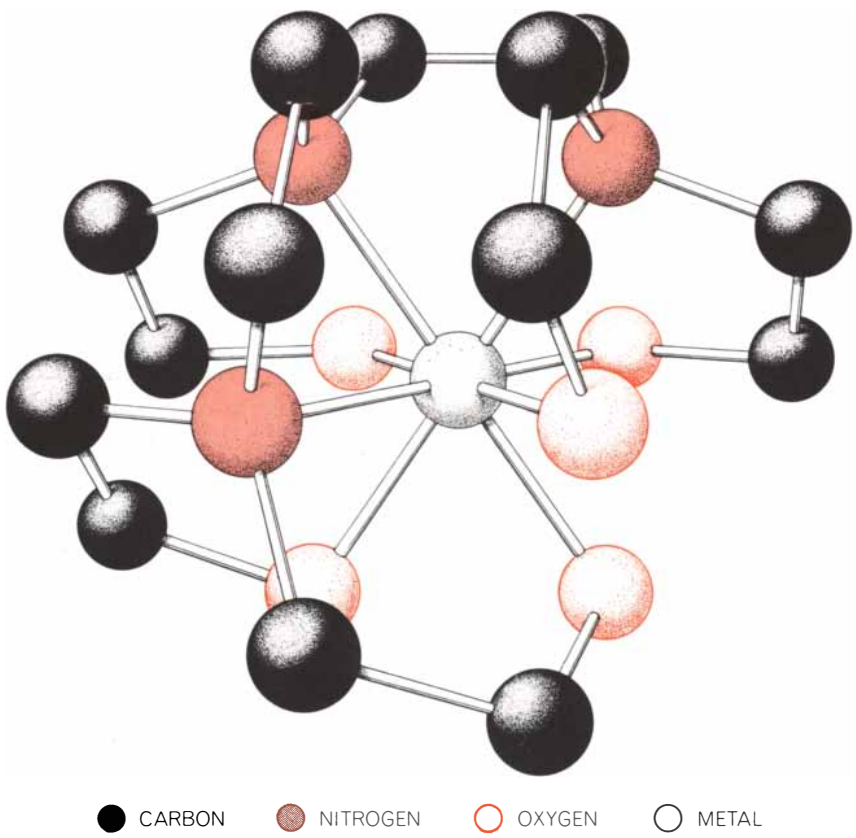
The medical importance of chelating agents hinges on the fact that metals play many critical roles in the life of living organisms. In the human body metabolism depends not only on sodium, potassium, magnesium and calcium but also to a considerable degree on trace amounts of iron, cobalt, copper, zinc, manganese and molybdenum. On the other hand, certain other metals, even in minuscule amounts, are highly toxic to the body. It is apparent, therefore, that chelate drugs with appropriate properties could play several different therapeutic roles. Various chelating agents might be designed (1) to seek out toxic metals and bind them in compounds that will be excreted, (2) to deliver essential trace metals to tissues or substances that require them and (3) to inactivate bacteria and viruses by depriving them of metals they need for their metabolism or by delivering metals to them that are harmful. All three of these hopes have been realized.

Obviously in the design of chelate drugs for specific purposes everything depends on the relative affinity of the chelating agent for the given metal. To be effective in removing a metal, the drug must seize and hold it more strongly than any biological substance that might be available to form a compound with the metal. To deliver a metal to the cells, on the other hand, the grip of the carrier drug must be comparatively loose; that is, the drug's affinity for the metal must be less than that of the substance to which the metal is to be surrendered. Hence an important part of the research on chelating agents has been the development of ways to measure the affinities between various substances and metal ions.

The measurement begins with determination of the intensity of interaction of the chelator with the metal. This measure, which is based on the amount of chelate formed by given concentrations of the reactants, is called the formation constant. That measurement in itself is not very meaningful, because when the chelating drug is introduced into a living organism, many interfering factors come into play. Substances in the organism will compete with the drug for the metal ion in which we are interested; conversely, various ions in the organism will compete with this ion for combination with the chelator. For ex-




**FIRST SYNTHETIC CHELATE, patented in 1935 by the German chemist F. Munz, is EDTA, an abbreviation for ethylenediaminetetraacetic acid. Its molecule has six ligand atoms, two nitrogen and four oxygen (*color*). These atoms are shown bonding an atom of lead, a toxic metal for which EDTA has an affinity that was first used medically in 1951.**




**RADIOACTIVE METALS are efficiently sequestered by another chelate, DTPA, which has a total of eight ligand atoms in every molecule, three nitrogen and five oxygen (*color*).**

ample, although the affinity between EDTA and mercury in the test tube is strong, in the body it is so weakened by interfering factors that EDTA is ineffective against mercury poisoning. On the other hand, EDTA is quite effective in eliminating zinc from the body, because of the relative weakness of competing or interfering factors, even though EDTA's absolute affinity for zinc is about a million times less than its affinity for mercury!

Among the factors that affect the action of chelating agents, one of the most important is the concentration of hydrogen ions in the medium, that is, its acidity. The hydrogen ions compete with metal ions for the chelator. In the case of EDTA the chelating ability of the compound depends mainly on the quadruply ionized form of the molecule: the form that has had four hydrogen ions removed. Hence in an acid medium, where many hydrogen ions are available to recombine with the molecule, EDTA loses much of its potential effectiveness. Calcium ions also compete with metal ions. Once in the blood, in fact, a chelate is rapidly converted to its calcium form, and the metal ions must be able to displace calcium if they are to become bound.

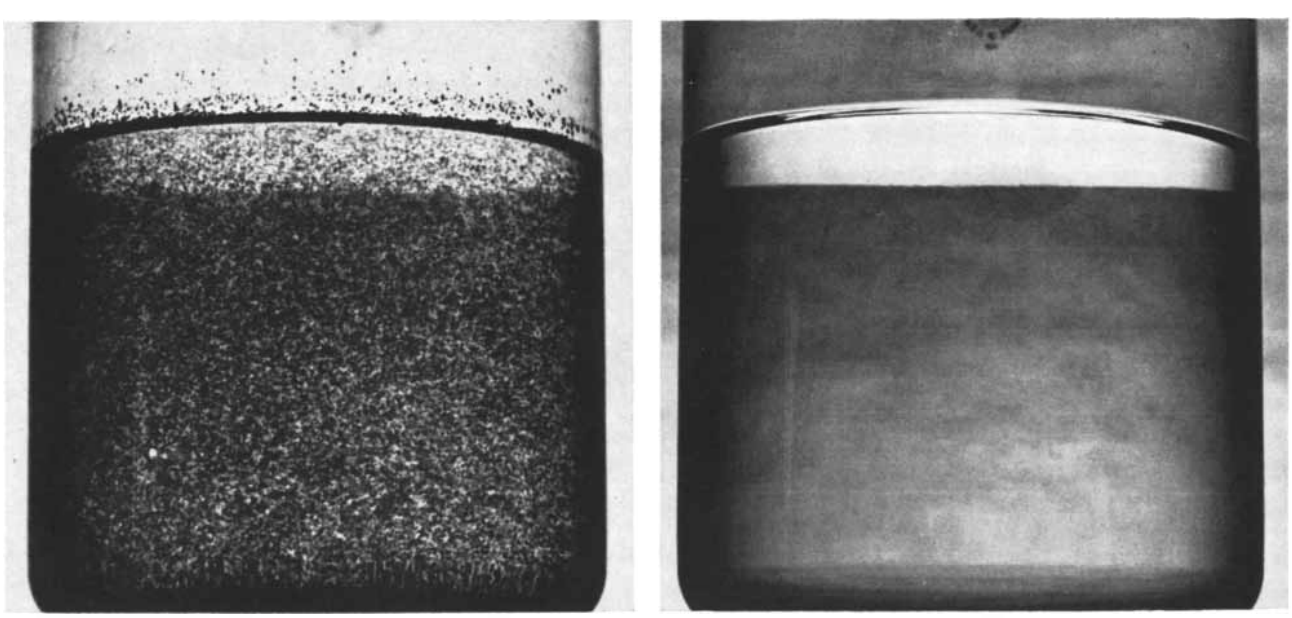
The hydroxide ion ($OH^-$), hydrogen's partner in the molecule of water, also is a factor to be reckoned with. Hydroxide ions combine with polyvalent metal ions (a process called hydroxylation); consequently they interfere with chelation of these metals. In the case of the trivalent iron atom the interference by the concentration of hydroxide ions at neutral acidity reduces the number of iron atoms that can be chelated by a factor of 100 million. Divalent copper, which is less prone to hydroxylation than iron, is chelated more strongly than iron by many chelating drugs.

Fortunately the allowance that must be made for these various interferences with a chelating agent can usually be computed in a simple way. It generally amounts to the sum of the interfering factors, or "side reactions," and often one factor is so dominant that the others can be disregarded. Subtraction of the interference from the absolute "formation constant" of a particular chelate yields a value that is called the "effective constant," or effective avidity, of the combination—which of course is not actually a constant but varies with the milieu in which the metal ion and chelating agent are to combine.

The effectiveness of a chelating drug cannot be evaluated solely on the basis of the chemical affinity between the drug and its target ion. We must also consider how readily the drug can reach its target. Sometimes the drug must penetrate a layer of fatty molecules to make contact with the metal; in such cases it is essential that the drug molecule be soluble in fat. Often the drug molecule must be designed so that it has no bulky groups that will prevent it from penetrating a protein that holds the metal ion, or it must be shaped so that it will fit into the site of the ion. Another factor to consider is that the drug may be inactivated or destroyed by enzymes acting on it in the body. The drug must also be administered in a form that will not do injury to the body—for example by removing calcium from the blood or robbing tissues of other essential metals.

The principal chelate drugs that have been studied so far are presented in the illustration at the bottom of pages 44 through 47, which shows their chemical formulas, their properties and their uses. Let us consider now in some detail the functions these agents may perform. We shall start with the first use to which chelating drugs were deliberately applied: as antidotes to metal poisons.

Acute metal poisoning afflicts more than 1,000 persons a year in the U.S. With our present technology spewing enormous quantities of metals into the environment, all of us carry some load of toxic metal in our bodies, but harmful effects are recognized mainly in acute cases. Probably the chief contributor to this load of metal is lead. We are exposed to lead in the air from the combustion of leaded gasoline and to deposits of the metal in our food and water. Clair Patterson of the Massachusetts Institute of Technology has estimated that the average adult American takes in about 400 micrograms of lead a day from these sources and carries a constant load of about 200 milligrams of lead in his body. About a million tons of lead is released into the U.S.



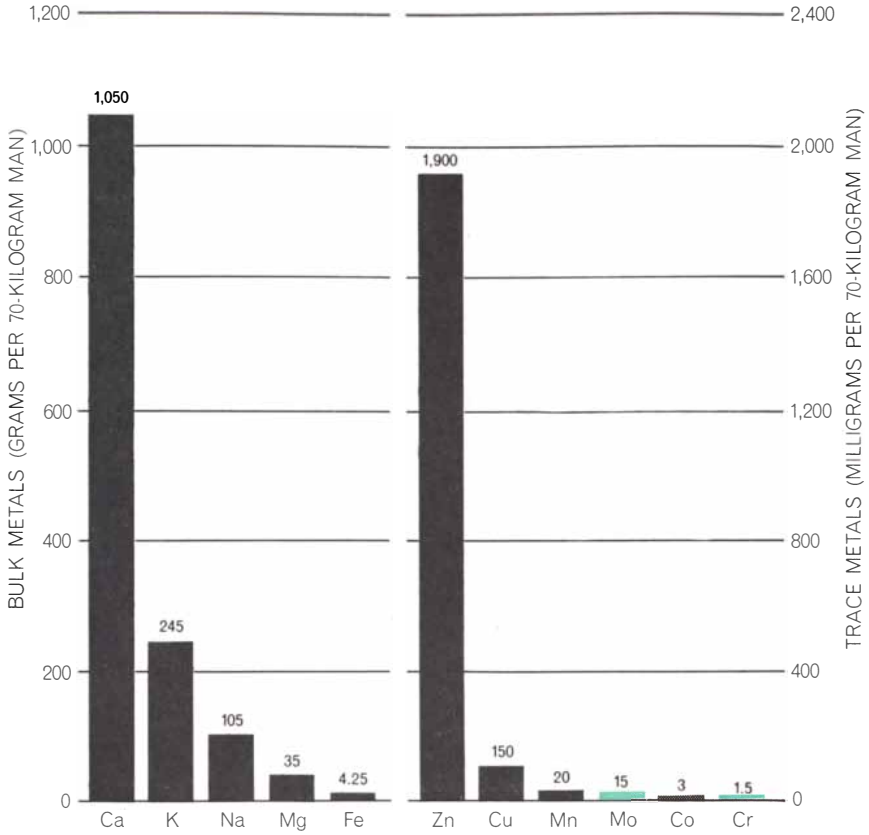
**ACTION OF A CHELATE** is visibly demonstrated in these two photographs. A beaker of water (*left*) is clouded by an insoluble iron compound. When EDTA is added, its ligand atoms begin to sequester the atoms of iron and the water soon turns clear (*right*).

environment annually, mainly from automobiles.

Acute attacks of lead poisoning occur most often in slum areas, where old, flaky lead paint is the main hazard. Most of the victims are children, because of their propensity for chewing on objects. A slum area in Cleveland is known as the "lead belt": 85 percent of the acute lead poisoning cases in the city occur in this area. Urine examinations conducted among children living in old, substandard housing in this belt showed that 10 times as many of them suffered from dangerous levels of lead poisoning as did children who lived in a new housing project constructed in the same slum area.

The first known treatment of lead poisoning with a chelating drug took place in the Children's Hospital in Washington in June, 1951. The patient was a three-year-old boy who had had convulsions and showed signs of brain damage from the poisoning. Two pediatricians, Samuel P. Bessman and Hugh Ried, with the counsel of the Georgetown University biochemist Martin Rubin, decided to try treatment with EDTA. Given a series of doses of the calcium disodium salt of this compound at frequent intervals, the boy recovered from the poisoning by the third day.

EDTA has become the treatment of choice for lead poisoning. It can increase the body's excretion of lead through the urine dramatically, sometimes as much as fortyfold. In cases of acute poisoning EDTA has been known to cause the patient to excrete, within the first day, more than three milligrams of lead. If this amount of lead were circulating in the body unchelated, it could be lethal.




**TRACE METALS essential to human health are divisible into the five present in "bulk" quantities (*left*) and the four that are found in far smaller amounts (*right*). Molybdenum and chromium (*color*) may also be essential. Of the total 4.25 grams of iron in the body, a two-milligram fraction actually functions not as a bulk metal but as one of the smaller traces.**

Studies of the performance of EDTA have disclosed the general pattern of action by which a chelate drug combats a metal poison. The drug combines with the metal to form a chelate that is harmless, stable and readily excretable in the urine or feces. The first dose of the drug generally brings on a large increase of excretion of the target metal from the body. In response to the second dose the amount of metal eliminated usually is not as large, but it represents an extraction of the same proportion of the metal remaining in the body. Experience with EDTA has shown that it is generally advisable to suspend administration of the drug temporarily after the first few days of dosage, not only to avoid possible harmful effects of the drug but also to allow the body to redistribute the metal to more accessible locations in its tissues. After a suspension of several days the first dose of the drug in the new series may extract as much metal from the body, in absolute amount, as the original dose did at the beginning of the treatment. Eventually the course of treatment eliminates the excess metal from the blood and tissues and reduces the metal to the normal level.

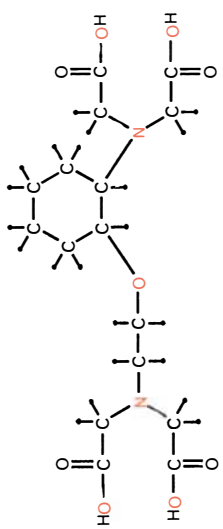
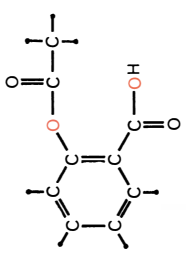
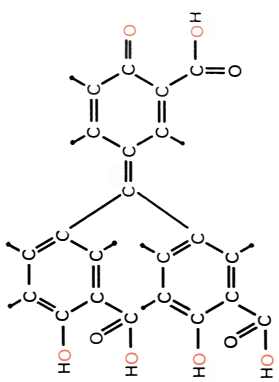
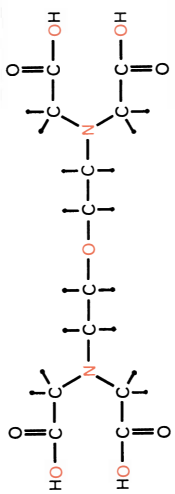
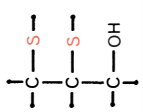
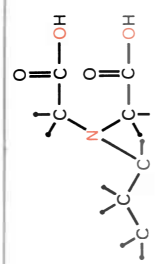
EDTA and other chelate drugs can be used to probe the body for the possible presence of poisoning that may not show clear outward symptoms. In one such investigation a group of children suspected of having lead poisoning was compared with a control group. Before administration of the drug the level of lead in the urine of both groups was about the same: it ranged from 15 to 24 micrograms per liter in each group. After the injection of EDTA the excretion of lead by the control group rose to an average of 165 micrograms per liter, as was to be expected, because the drug will extract lead even from persons with "normal," or tolerable, levels of the metal. In the "suspected" group, on the other hand, the excretion of lead jumped to an average of 995 micrograms per liter.

It may surprise some people to learn that iron, as well as lead, can act as a poison in the body. In trace amounts it is essential; in excess it can be fatal. At least 12 children a year in the U.S. die of eating the sugar-coated, iron-containing pills (ferrous sulfate) that their mothers may be taking for anemia. In Britain this raiding of the medicine cabinet for ferrous sulfate tablets accounts for about 10 percent of all the fatal poisonings of children. In South Africa the Bantu, who drink a beer made in iron vessels and thus ingest 50 to 100 milligrams of iron daily, commonly suffer from many ailments partly induced by iron, including cirrhosis of the liver, by the time they reach middle age.

There is a rare hereditary disorder, called hemochromatosis, that results in extremely high accumulations of iron in the body. In the liver alone the iron may rise to 40 grams, whereas normally the entire body of a healthy person contains no more than four grams of iron. The usual treatment prescribed

for sufferers from this disease has been regular bleeding, to remove iron from the body by means of the shed blood and to stimulate the production of red cells, which draws on iron in the other tissues. Obviously, however, the copious bleeding required is a drastic therapy that many persons cannot tolerate. The arrival of chelating drugs has brightened the outlook for victims of hemochromatosis.

For the removal of excess iron from the body the most effective chelating agent at the moment is a compound called desferrioxamine B. Derived from a substance first discovered in microorganisms in 1960, this compound forms a snakelike chain that coils itself around the iron atom, and it has a remarkable affinity for ferric (trivalent) iron. A hundred milligrams of desferrioxamine B can chelate about 9.3 milligrams of iron. A single intramuscular injection of 500 or 600 milligrams of the drug in the human body can increase a normal person's excretion of iron, usually about a tenth of a milligram a day, to a milligram or more a day. In a patient with iron poisoning, who excretes only about half a milligram a day without the drug, the same dose of the drug will raise the rate of iron excretion to as high as 20 milligrams a day. Another asset of desferrioxamine B is that it has comparatively little affinity for metals other than iron;

| NAME | FORMULA | USES |
|---|---|---|
| ACTA |  | Used experimentally in iron poisoning. |
| ASPIRIN |  | Used to reduce fever and for the relief of headache, muscle and joint pain and symptoms of rheumatic fever. |
| ATA |  | Used experimentally to reduce fever. |
| BAETA |  | Used in cases of strontium-90 poisoning. |
| BAL |  | Used in cases of arsenic, mercury, antimony and gold poisoning. |
| DCTA |  | Used experimentally in iron poisoning. |

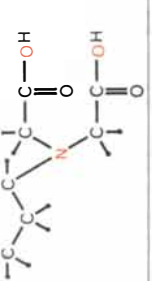
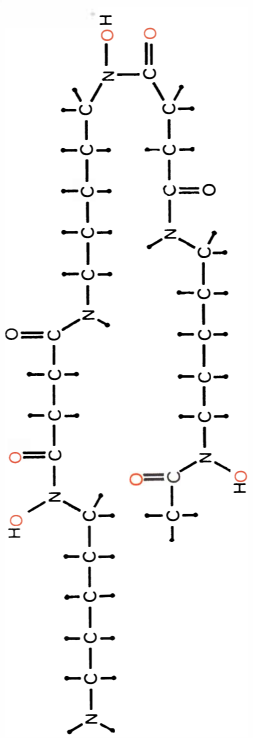
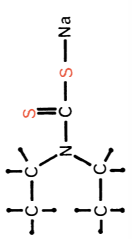
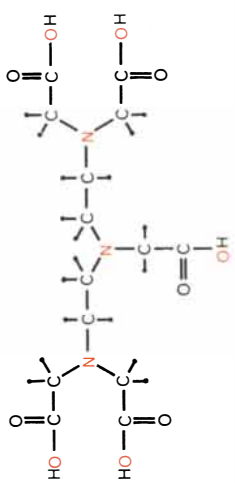
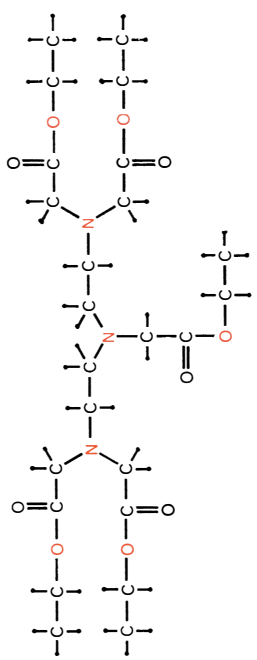
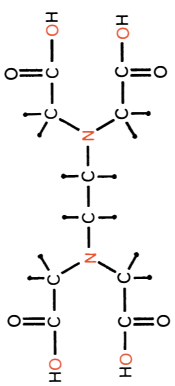
**CHEMICAL FORMULAS of the 22 most prominent chelate drugs are presented on these and the next two pages, together with brief descriptions of their present uses. The chelates are listed in the alphabetical order of their names or acronyms. The atoms in each**

consequently it minimizes the danger that prolonged administration of the drug will deplete the body of essential metals such as calcium.

The chelating agent DTPA is another good iron binder, often used in combination with desferrioxamine B. Chemists in Switzerland and Germany are now investigating a group of chelating compounds related to EDTA that may outdo desferrioxamine B as antiiron agents. These compounds, called DCTA and ACATA, have a higher avidity for iron and have shown themselves to be more effective in removing iron from the body in experimental animals.

In the case of poisoning by copper, the most serious problem is an inherited disorder called Wilson's disease. The copper content of the tissues rises to intolerably high levels, particularly in the liver and brain. By attacking the nervous system it produces tremors and uncoordinated movements, and the liver suffers irreversible damage. Children afflicted with the disease die within a few years.

In 1956 J. M. Walshe of the University of Cambridge found that a chelator could control this formerly incurable disease. The agent is penicillamine, a sulfur-containing amino acid, which has a very high affinity for cuprous (monovalent) copper. It can be taken by mouth, and the dextrorotational form of

| | | | | | |
|---|---|---|---|---|---|
|  |  |  |  |  |  |
| | Used in cases of iron poisoning. | Used in cases of nickel poisoning. | Used in cases of poisoning by radioactive metals, plutonium and thorium and in cases of iron poisoning. | Particularly efficient in removing polymeric plutonium from the liver. | Used in cases of lead poisoning and in the treatment of skin irritations produced by chromium, nickel and copper. Also used in treatment of atherosclerosis and for removal of calcium in digitalis poisoning. Many other applications in the experimental stage. |
| | DESFERRIOXAMINE B | DITHIOCARB | DTPA | DTPA-E | EDTA |

**molecule that are most likely to contribute electrons to the metal ion that is sequestered are indicated in color in each diagram. A dot at the outer end of any bond represents an atom of hydrogen. Both DTPA and EDTA are shown in three dimensions on page 41.**

the compound can be used in doses of up to a gram a day for years without serious side effects. Its action is slow: it may take a year or more for the patient to show substantial improvement. Remarkable recoveries have been reported, however, in case after case.

Chelating antidotes have been found for several other metal poisons. BAL, the antiarsenic agent, is effective against acute mercury poisoning and also poisoning by gold. It is impotent against chronic poisoning by mercury—in fact, it may even aggravate the patient's condition—but the chronic form of the ailment has been treated successfully with a modification of penicillamine called N-acetyl-DL-penicillamine. Chelating agents are even employed to treat skin irritations produced by metals. An ointment containing EDTA or dithiocarb can, if promptly applied, prevent a nickel-induced dermatitis known as "nickel itch." The EDTA ointment can also relieve skin irritation caused by chromium. There is an ointment that relieves the lesion of poison ivy; employing a metal salt of zirconium, this agent presumably acts by chelating oleoresin, the irritating substance in poison ivy and poison oak.

Of all the metal poisons that may enter the body, the most dangerous are radioactive isotopes. Particularly hazardous are the products of nuclear re-

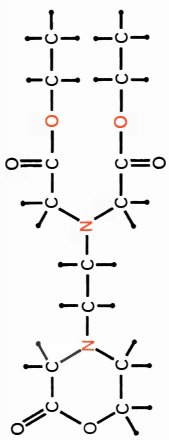
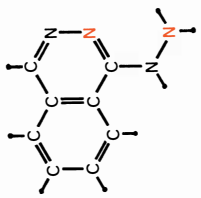
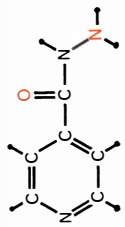
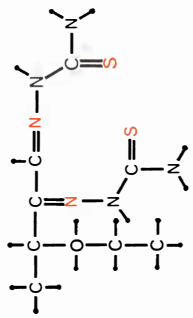
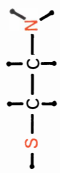
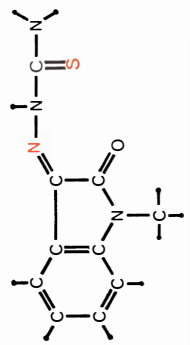
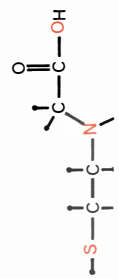
| NAME | FORMULA | USES |
|---|---|---|
| HEDTA-E |  | Particularly efficient in removing radioactive metals and lead from the liver and kidney. |
| HYDRALAZINE |  | Used to lower blood pressure. |
| ISONIAZID |  | Used in the treatment of tuberculosis. |
| KTS |  | Used experimentally in the treatment of cancer. |
| MAA |  | Used for protection against ionizing radiation. |
| MARBORAN |  | Antiviral in action; used for protection against smallpox. |
| MEIDA |  | Used experimentally in cases of mercury and |

**CHART IS CONTINUED from the preceding two pages. Some of the chelates, such as Marboran and oxine, are used against organic agents such as viruses and bacteria. Oxine derives its germicidal power from a reversal of the normal chelation process; it transports**

actions such as plutonium, strontium 90, cesium 137 and certain rare earths. Even in very small concentrations the radiations from radioisotopes can be deadly, and it is imperative to remove them from the body as soon as possible.

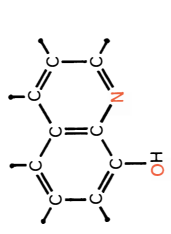
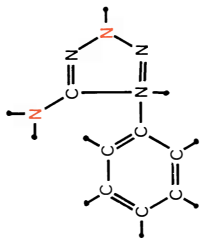
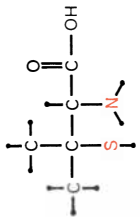
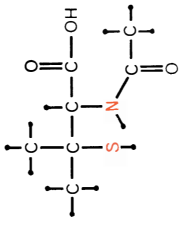
A chelating agent cannot serve as the first line of attack on a radioactive element that has been ingested into the stomach. By incorporating the element into a soluble compound the chelator would facilitate its absorption into the body tissues. The first concern must be to try to block the radioactive poison from passing out of the alimentary tract into the bloodstream. The best immediate treatment, therefore, is to introduce into the stomach a substance that will form an insoluble compound with the radioactive metal so that it will be excreted promptly in the feces. Cesium 137 can be trapped in such a compound by the iron-containing inorganic salt called Prussian blue; strontium 90 can be similarly bound by sodium alginate, a seaweed product.

Once the radioisotope has invaded the body tissues, the problem of removing it becomes more difficult, and it is here that the metal-seeking chelators have proved of great value. EDTA, the first synthetic chelator tested for this purpose, had pronounced success in helping the body to get rid of plutonium and many other radioactive materials, notably the trivalent rare earths. DTPA has now supplanted EDTA as the preferred drug, because anything EDTA can do DTPA usually can do much better. Its principal advantage is that its molecule has more chelating sites, so that the metal atom is bound more firmly.

W. D. Norwood of the Pacific Northwest Laboratory has reported that a single injection of DTPA can increase the body's excretion of plutonium a hundredfold. He relates that, in a case in which the DTPA treatment was resumed several months after it had been discontinued, the first dose again produced a spectacular increase in the excretion of plutonium. Evidently the plutonium remaining in the body had migrated to more accessible sites.

The attempt to find a chelating drug to remove strontium 90 has been encumbered by the stubborn chemical fact that most chelators bind calcium more strongly than they do strontium; hence they rob the body of the wrong element. EDTA and DTPA fail to remove strontium from the body in any significant amount. Recently a compound related to EDTA, called BAETA, has been found capable of removing substantial amounts of radiostrontium if the drug is given soon after the strontium ingestion, according to a report by Herta Spencer of the Veterans Administration Hospital in Hines, Ill. I have also found that zirconium citrate can be effective in the removal of strontium 90.

The principal danger of some of the radioisotopes, particularly strontium 90, is that they give rise to bone cancer. In experiments on animals Joseph F. Kuzma of the Marquette University School of Medicine found that zirconium citrate reduced the incidence of bone tumors in animals that had been injected with strontium 90. My former colleagues at the Argonne National Laboratory and I demonstrated that DTPA, administered to remove plutonium from the body, also has the effect of preventing bone tumors. In our laboratory at the University of Pittsburgh we

| | | | | |
|---|---|---|---|---|
| | Antibacterial in action. | Used in the treatment of rheumatoid arthritis. | Used in cases of copper poisoning (Wilson's disease) and lead poisoning. Inhibits tumor growth in mice. | Used in cases of mercury poisoning. |
| =O |  |  |  |  |
| OXINE | PAT | PENICILLAMINE | PENICILLAMINE-N-ACETYL | |

**metal to an infected area and then releases it. Most of the chelates, however, are used to treat cases of acute metal poisoning, the number of which averages 1,000 a year in the U.S.**

are making a systematic survey of the problem of removing radioelements with chelating agents, in various chemical states of the element and the agent and under various conditions of accessibility of the target element in the body.

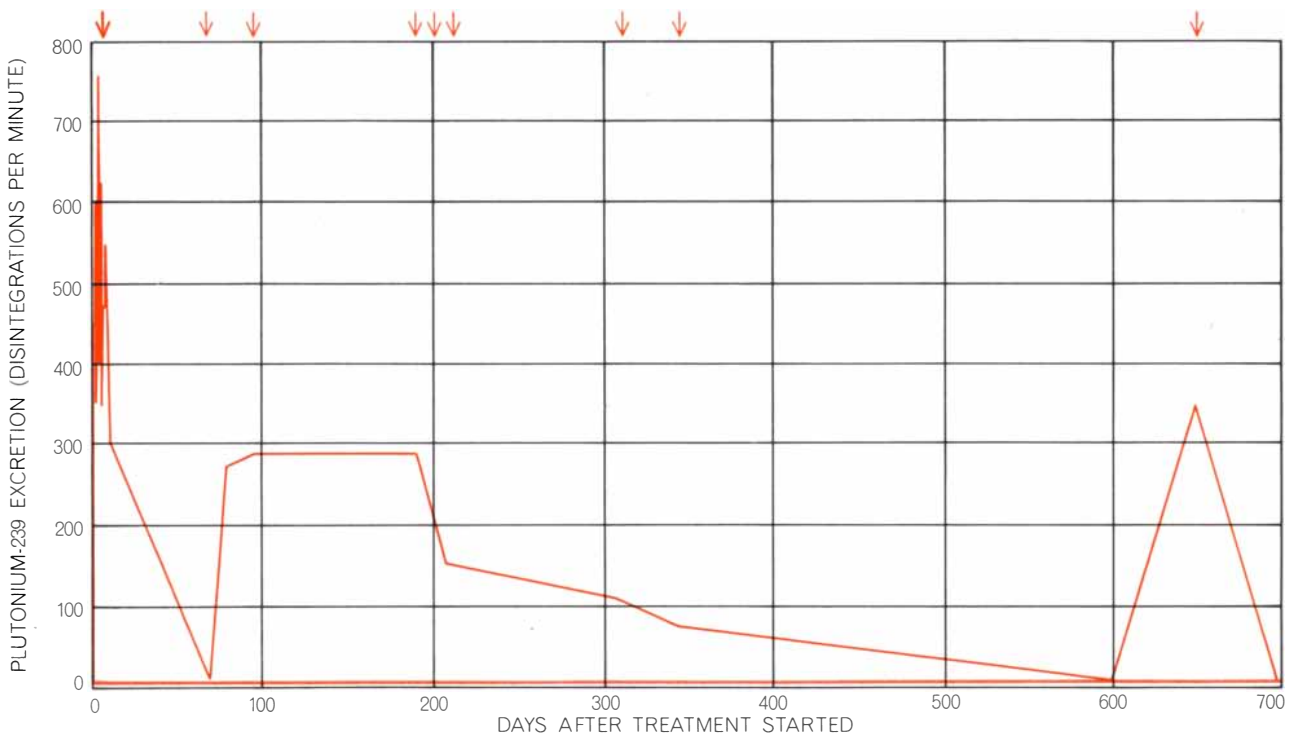
In all the applications of chelate drugs that I have discussed so far, the function of the drug is simply to hunt down a metal poison and carry it off. We shall now consider uses in which the action of the drug is more subtle—and less clearly understood.

It has been known for some time that certain chelating agents that can chelate copper, notably sulfhydryl compounds, are capable of protecting experimental animals against even lethal doses of ionizing radiation. Just why they should give this protection was a mystery. Because the most effective radioprotective drugs reacted preferentially with cuprous copper, it occurred to me that the chelating drugs might act to protect the integrity of enzymes bound to cuprous copper in the cell by forming a complex that shielded the copper from the oxidizing effect of the radiation. Thus protected, the enzymes would remain available to help later in the repair of the radiation damage to the cell. This hypothesis implied, among other things, that a chelating drug effective in protecting against radiation must be capable of making contact with binding sites of the copper in the enzyme-copper complex and that it must form a stable chelate ring with the copper. Those requirements in turn implied that the chelating agent must have certain structural properties, and accordingly it should be possible to predict in advance whether or not a given agent would protect against radiation.

Experiments with various agents provided support for the validity of this hypothesis. For example, the sulfhydryl compound called mercaptoalkylamine (MAA) is a copper chelator. The hypothesis predicts that this molecule will afford radioprotection only in versions in which the number of $CH_2$ groups is less than two, allowing the molecule to form a strong chelate ring of five or six members with copper. Tests show that this is indeed the case: when the molecule contains two or more $CH_2$ groups, it has almost no radioprotective effect. Again, the theory predicts that a sulfhydryl compound will be radioprotective only if it has a sulfur bond that is free to attach to the copper atom. There is an effective protector against radiation, called AET, that seems to contradict the hypothesis, because both sulfur bonds are occupied. It turns out, however, that in the body the AET molecule is rapidly transformed to another form, called MEG, in which a sulfur bond opens up [*see illustration on opposite page*]. Another confirmation of the copper-binding hypothesis of radioprotective action has been provided by the finding that injection of a copper chelate of MEG (that is, the compound already containing copper) gives little protection against radiation, whereas the chelate of MEG with zinc, which can be displaced by copper because of MEG's stronger affinity for copper, is nearly as effective in protection against radiation as MEG itself.

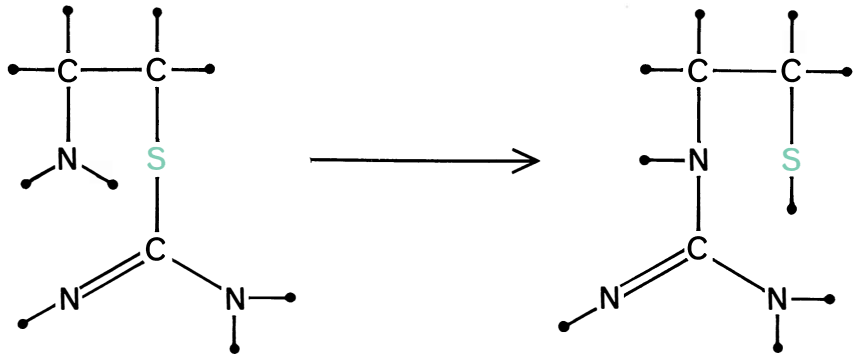
In their role as captors of metal atoms, chelate drugs have shown that they can sometimes be helpful against cardiovascular diseases. The nature of their action in this area is obscure; all that can be said is that calcium is known to be involved in the functioning of the heart and that trace metals seem to play roles in the metabolism of cholesterol and to affect the rhythm of the heartbeat.

EDTA has been used extensively to




**ELIMINATION OF PLUTONIUM, 36 months after exposure, was greatly enhanced by doses of the chelate DTPA (*arrows*). The rate of plutonium excretion in the patient's urine when untreated is shown as a horizontal line. The peaks produced by the treatment (*left and right*) imply that the DTPA first chelated most of the plutonium located in readily accessible body sites but could not continue to act at a high level of efficiency until additional plutonium became accessible as a result of redistribution in the body tissues.**

treat attacks of cardiac arrhythmia (irregularity of the heartbeat). The drug lowers the level of calcium in the blood, and careful administration of EDTA's sodium salt has been found to give relief in about 50 percent of cases and to restore the normal beat in some cases. EDTA has also been useful for treatment of overdoses of digitalis, which can be lethal when the calcium level is high. Several medical groups have reported that EDTA has given relief in cases of atherosclerosis and angina pectoris. Nevertheless, it must be said that in the field of cardiovascular disease the chelate drugs are only in the early trial stage, and it is still uncertain to what extent chelation itself is responsible for their effects.




**RADIOPROTECTIVE AET, a sulfhydryl compound (*left*), in theory should not offer any protection because both bonds of its potential ligand sulfur atom (*color*) are in use. In the body, however, AET is rapidly transformed into MEG (*right*), thus freeing a sulfur bond.**

Let us turn now to the types of drug action in which the function of the chelator is not to remove metal atoms from the body but to deliver them.

This story begins with an antiseptic called 8-hydroxyquinoline, or oxine for short, which has been used for many years as a bactericide and fungicide. It was noted long ago that the compound was effective only in combination with iron or copper. Adrian Albert and his associates at the Australian National University explored the nature of its action. They found that in a metal-free medium of distilled water oxine did not kill the test organism (*Staphylococcus aureus*, the bacterium found in boils). It did kill the bacteria when they added iron to the water or when the medium was a broth containing traces of iron. When they abolished oxine's chelating ability by changing the structure of the molecule, it lost its bactericidal action. Similarly, they found that they could eliminate its antiseptic action merely by making the molecule insoluble in fats. It also developed that oxine could be transformed from a bactericide to a fungicide (without losing its ability to kill bacteria as well) by making it a chelator of copper instead of iron.

A dose of oxine chelate can kill bacteria within an hour. Curiously, the more the size of the dose of the drug is increased, the less effective it becomes. If the drug is raised to high concentration, it may not show any effect on the bacteria for at least 24 hours. The reason is that a large excess of the compound delays the chelate's release of free iron (or copper), which is the agent that kills the bacteria.

Many of the well-known antibiotics and synthetic bactericides—penicillin, streptomycin, bacitracin, the antitubercular drug isoniazid, the tetracyclines, the thiosemicarbazones and others—are chelating agents. Often the addition of a metal to an antibiotic, forming a chelate, improves its properties as a drug, because it facilitates the spread of the drug through the body. Although the antibiotics are known to be capable of chelation, little has been learned so far about how this property comes into play in their bactericidal action. Nonetheless, in view of the fact that chelation seems to be a common property of the potent drugs, it seems a good idea to test all chelators routinely as potential weapons against bacteria and other microbes. There are even a few chelating agents that are more or less effective against viruses; among them is Marboran, the new antismallpox drug that proved highly useful in a smallpox epidemic in Madras, India, in 1963. Among 1,101 exposed persons who were given Marboran only three mild cases of smallpox developed, with no deaths, whereas in a matched control group of 1,126 who did not receive the drug there were 78 cases with 12 deaths.

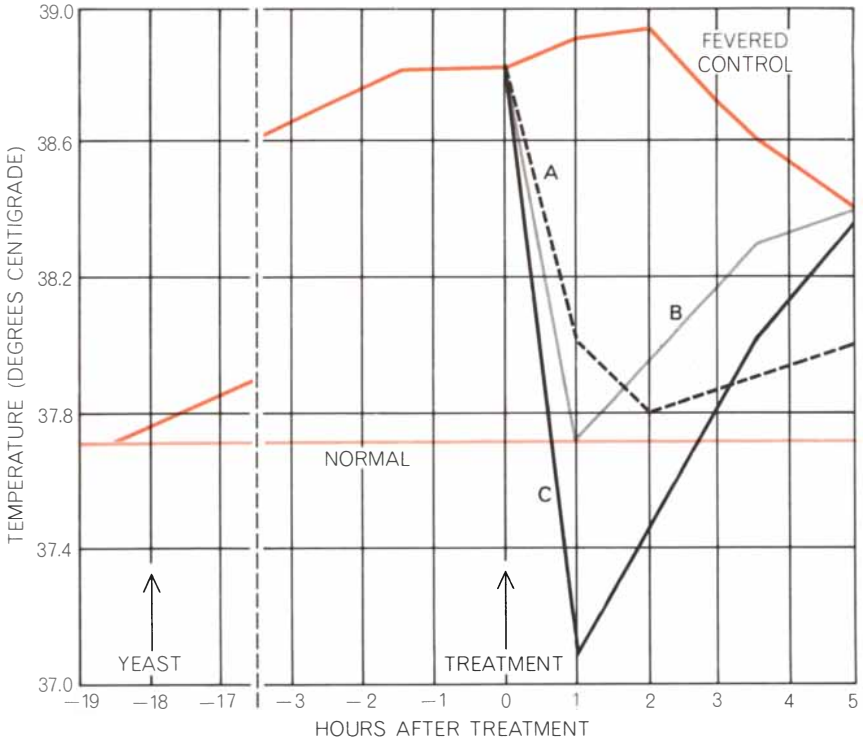
We can take a wider view of chelation, thinking of it not strictly in terms of specific diseases but in the broad perspective of the body's basic health and generalized disease processes. Two instruments are available for examining this view: on one hand, the multipurpose drug aspirin; on the other, the many-sided disease cancer.

More than 16 billion tablets of aspirin are taken yearly in the U.S. to relieve headaches and other pains, reduce fever, treat rheumatic fever, relieve rheumatoid arthritis and deal with a wide variety of other ailments. Theories about how aspirin produces its effects are vague. The prevailing hypothesis has been that the salicylates (that is, aspirin and the other drugs of its class) act to stimulate metabolism and also the adrenal glands (in much the same manner as cortisone and ACTH).

That the salicylates might owe their effects to chelation was first suggested in 1951 by James Reid and his colleagues at the University of Glasgow. They had found that isomers of salicylic acid that lacked the ability to form chelate rings did not possess the therapeutic properties of the drug. On the other hand, all drugs with a wide spectrum of drug action like aspirin's (including cortisone, antipyrine and ACTH) are capable of chelation.

I suspected that the various effects of the salicylates might be accounted for on the basis that the drugs delivered copper to the body cells. It was known that in most human disorders, including infectious disease, rheumatoid arthritis and cancer, the amount of copper in the blood rises to two or more times the normal level. Simple removal of the excess copper from the blood (for example by a drug such as EDTA) does not relieve pain or reduce fever as aspirin does. It seemed to me, therefore, that the flood of copper into the blood under stress might reflect a loss of essential copper from the cells, and that aspirin as a chelator might repair this biochemical "lesion" by picking up copper from the blood and returning it to the cell sites from which it was lost.

I was then at the Argonne National Laboratory, and I tested the hypothesis experimentally with the collaboration of two colleagues, Marcia W. Rosenthal and Joan F. Markley. If the theory was correct, then perhaps the simple injection of copper salts into the blood-




**ACTION OF ASPIRIN in reducing fever is contrasted with the action of ATA, a similar chelate. The yeast-induced fevers of rats were lowered and kept near normal for some hours by aspirin, regardless of the size of dose (*A*). Small doses of ATA had similar but briefer effect (*B*), but larger doses brought the rats' temperatures below normal (*C*). Unlike the ATA molecule, the molecule of aspirin is small, enabling it to enter the brain. This contact with the central nervous system may be the reason that aspirin differs from ATA in action.**

stream might result in delivery of copper to the cells and thus show an effect like that of aspirin. We injected copper salts intravenously into feverish rats and found that this did indeed reduce the animals' fever. The salts of other metals, such as magnesium or iron, failed to produce this effect. On the other hand, injection of the salicylic chelate of copper was much more effective than injection of the simple copper salts by themselves.

Did salicylic acid act only directly on the target cells or did it produce its effects primarily through action on the central nervous system? To investigate this question we resorted to a compound, aurintricarboxylic acid (ATA), that possesses the chelating properties of salicylic acid but cannot enter the brain because its molecule is too large to pass through what is called the blood-brain barrier. This drug succeeded in reducing the temperature of experimental animals, but its action was short-lived and, unlike salicylic acid, it simply lowered the body temperature by a certain amount (whether or not the animal had a fever) instead of stabilizing the temperature at a specific level. Thus the experiments indicated that the antifever effect of salicylic acid is attributable largely to its action on the brain.

If a copper-chelating drug can reduce fever by bringing copper to the cells, by the same token such an agent, in a healthy person whose temperature is normal, might with repeated, long-term administration induce fever or symptoms of inflammation by removing copper from the cells. This, indeed, has been demonstrated to happen. D. A. Gerber of the Downstate Medical Center of the State University of New York produced symptoms much like those of rheumatoid arthritis in healthy people by administering a copper-binding drug, hydralazine. He also found that patients with rheumatoid arthritis have a higher than average amount of natural copper-chelating substance in their bodies, as shown by their excretions. By screening some 900 copper-chelating compounds Leon L. Wiesel and his collaborators at Brooklyn Hospital found one, 1-phenyl-5-amino-tetrazole (PAT), that has proved beneficial in many rheumatoid arthritis patients who had not responded to other drugs.

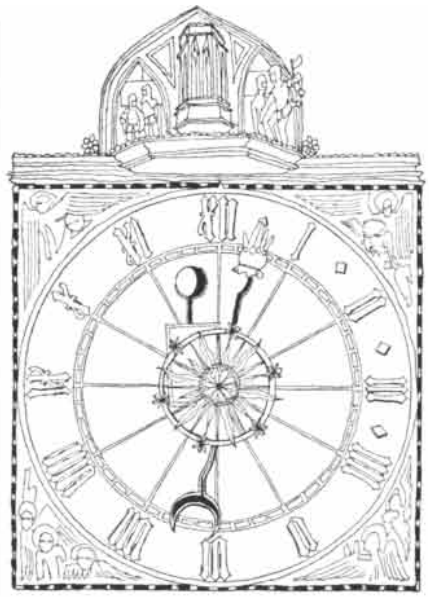
The diseases of cell malignancy suggest the biological importance of chelation from another point of view. Many of the drugs that show some activity against cancer possess the chelating property. Various cell structures, including the nucleus, are known to contain trace metals. Some chelating agents, as we have noted, act against viruses. All of this suggests that metal chelation may well be an important factor in cancer. A chelate of copper with a compound called KTS (which resembles some of the antiviral agents) has been found to check the growth of tumors in rats and mice and is now being tested clinically.

On the assumption that viruses are associated with many types of cancer and contain proteins and nucleic acid units capable of chelation, Stanley Kirschner of Wayne State University and his associates proposed that metals might destroy or diminish viral activity. In order to carry the lethal material near or into a virus, they tested metal complexes in which the coordinating agents themselves were anticarcinogens. They found that both the platinum and the palladium complexes of 6-mercaptopurine destroyed the experimental cancers adenocarcinoma 755 and sarcoma 180. These promising experiments are continuing, and it is planned to incorporate ions of radioactive metal into the complexes in order to augment their capacity to destroy cancer growths.

Just how cancer and chelation may be connected is still a matter of conjecture. All that can be said at present is that chelation and metal ions apparently do play a definite role in the cause and treatment of malignancy.

In general, in the field of medical chelation we are still only feeling our way. As in the other branches of chemotherapy, the finding of effective chelate drugs is mainly in the trial-and-error stage. The investigation of these drugs is, however, turning up valuable clues to the roles and locations of trace metals in the body and is providing information on the nature of various diseases and basic principles for the design of drugs. It even suggests that ways may be found to induce the body to produce its own curative chelating agents. For example, one of the natural chelators is citric acid. By administering a certain metabolic inhibitor to rats we have caused them to increase the amount of citric acid in their tissues to 10 or more times the normal level, with the result that the rats have been able to rid themselves of lethal doses of lead—a result that massive injections of citric acid into their blood had failed to accomplish.

# SCIENCE AND



## *One Man's Trash*

Control of pollution has become a problem of such urgency, according to a committee of the National Academy of Sciences, that "large-scale experiments" are justified to deal with it. "Our whole economy," the Committee on Pollution said, "is based on taking natural resources, converting them into things that are consumer products, selling them to the consumer and then forgetting about them." In fact there are no "consumers" but only "users," and the time has come to begin devising "the ultimate system that closes the loop from user back to resource and reuse."

So far hardly any thought has been given to such a system, the committee said. Disposal is based on throwing things away, but "as the earth becomes more crowded there is no longer an 'away,'" because "one person's trash basket is another's living space." Pollutants from the burning of fossil fuels are being dumped into the atmosphere of the U.S. at a rate of 125 million tons per year, according to the committee, and at the present rate of increase this amount would double by 1980 and double again by the year 2000. By 1980 there would be enough waterborne waste to consume all the oxygen in all 22 river systems of the U.S. at low water. Per capita production of trash—up from 2.75 pounds per day in 1920 to 4.5 pounds per day in 1965—is increasing at the rate of about 4 percent a year.

The committee, which was headed by Athelstan F. Spilhaus of the University of Minnesota, recommended Federal initiatives to bring about the application of modern technology to the control of pollution. Among the ideas it suggested were using organic wastes to fertilize barren land and segregating metallic wastes so that they can be reused. The committee also proposed the formation of a National Commission for Environmental Protection, to be appointed by the President, and of regional groups to spur action on pollution.

## *Insect Hormones Synthesized*

Two hormones that regulate insect growth and metamorphosis are the molting hormone ecdysone and the juvenile hormone. Both have now been synthesized. The precise synthesis of ecdysone was worked out at the Syntex Research laboratory in Palo Alto, Calif., and a substance with juvenile hormone activity was synthesized at Harvard University.

Ecdysone, a steroid hormone produced by the prothoracic gland of insects, stimulates the successive moltings by which an insect larva changes into a pupa and the pupa into an imago, or adult. It has a direct, easily observed effect on single cells, causing the chromosomes to "puff" as specific genes are stimulated into activity [see "Chromosome Puffs," by Wolfgang Beermann and Ulrich Clever; SCIENTIFIC AMERICAN, April, 1964]. For this and other reasons ecdysone is an extremely useful steroid for biological investigation, but until now it has been available only in small quantities obtained by extraction from large amounts of insect pupae. In 1954 the German workers Peter Karlson and Adolph Butenandt purified the hormone; 10 years later Robert Huber and Walter Hoppe determined its structure by X-ray analysis. Now that structure has been confirmed by the Syntex group, headed by J. B. Siddall. They accomplished a 22-step synthesis that begins with a derivative of a plant steroid, stigmasterol, that is readily available. Their work is reported in *Journal of the American Chemical Society*.

The juvenile hormone is secreted by a pair of glands called the corpora allata. It is necessary for premetamorphic

development of the insect but its secretion must cease before the immature insect can metamorphose into an adult; the development of a metamorphosing insect exposed to minute traces of the hormone is lethally deranged. The potential of active extracts of the hormone as an insecticide was demonstrated 10 years ago by Carroll M. Williams at Harvard. Since it is fat-soluble, it penetrates an insect's body easily (unlike ecdysone, which is water-soluble and must therefore be ingested). Now Williams, John H. Law and Ching Yuan have produced a synthetic hormone by a simple two-step procedure, starting with the 15-carbon alcohol farnesol. The precise chemical structure of the synthetic hormone is still not known, they report in *Proceedings of the National Academy of Sciences*, but without any purification it kills a wide range of insect species. Unlike conventional insecticides, the synthetic hormone seems to have no effect on other animals. Moreover, Williams and Karel Sláma have found that certain variants of the hormone act only on individual species of insects, so its synthesis may lead to the development of selective, nontoxic insecticides aimed at specific insect pests.

*Pre-Neolithic Village*

The discovery of a 9,500-year-old village in Syria provides strong support for recent speculation that early man lived in permanent settlements long before he had learned to practice either agriculture or animal husbandry. In the fall of 1965 Maurits van Loon of the University of Chicago's Oriental Institute excavated 17 superimposed occupation levels covering a span of 1,000 years at Tell Mureybat, a five-acre village mound beside the Euphrates River some 200 miles northeast of Damascus. Preliminary analysis of plant and animal remains has now revealed that during their 10 centuries of residence the villagers ate nothing but wild foods. The bulk of their meat came from wild cattle, wild ass and gazelle; they also fed on fallow deer, boar, wolf and hare. They oven-roasted and also ground wild forms of barley and wheat and gathered wild lentil and vetch. Curiously

enough, in spite of the river location of the village, the inhabitants apparently did not eat fish.

The excavation covered 2,400 square feet, or about 1 percent of the entire mound; four or five dwellings were found in some levels. Other levels contained no dwellings but were composed of trash apparently thrown out of houses built elsewhere on the mound. Van Loon estimates that the number of families living in the village at any one time may have totaled 200. He finds it a mystery that a settled population of this size could have supported itself by hunting and gathering.

## *Helium from a Fireball*

Measurements made at Princeton University and the University of California at Berkeley have supplied the second and third "points" on a curve that may represent a cosmic background radiation left over from the primordial fireball associated with the beginning of the universe. The first evidence for such radiation was uncovered last year by Arno A. Penzias and R. W. Wilson of the Bell Telephone Laboratories in the course of trying to identify all sources of background noise that could be detected with a horn antenna operating at a wavelength of 7.3 centimeters. They found a residuum of noise that corresponds to the output of a black-body radiator that is at a temperature of $3.5 \pm 1$ degrees Kelvin, or $3.5 \pm 1$ degrees centigrade above absolute zero.

Now P. G. Roll and David T. Wilkinson of Princeton report in *Physical Review Letters* that they have found that the background flux at a wavelength of 3.2 centimeters corresponds to black-body radiation at a temperature of $3 \pm .5$ degrees K. and thus is consistent with the finding of Penzias and Wilson.

The third point, an indirect measurement, has been supplied by George Field of the University of California at Berkeley. Astronomers have known for some time that cyanogen molecules in interstellar space produce two absorption lines, indicating that some of the molecules are in a higher energy state than expected. The extra line represents absorption of radiation with a wavelength of 2.63 millimeters. The source of energy at this wavelength had been a puzzle.

Field and Neville Woolf of the Goddard Institute for Space Studies independently suggested that the absorbed radiation might be that left from the primordial fireball. If so, the second cyanogen line would provide another way of estimating the present temperature of the cosmic background radiation. Measurements made by Field show a temperature that also falls on the curve for a black-body radiator at about 3 degrees K. The significance of this third point is that it is for a wavelength much shorter than that of the other two points and that it falls in a region where the black-body curve has bent. The other two points lie on the straight-line region of the curve.

In the same issue of *Physical Review Letters* that contains the paper by Roll and Wilkinson, P. J. E. Peebles of Princeton discusses the implications of these measurements for the primeval abundances of helium and deuterium in the universe. Writes Peebles: "These [abundances] depend on two observable quantities, the temperature of the fireball radiation and the mean mass density in the universe." Using prevailing estimates of density and a fireball temperature that would have decreased to a present value of 3 degrees K., Peebles computes that the primeval abundance of helium was in the range of 27 to 30 percent by mass. In relative numbers of atoms helium would have exceeded deuterium roughly by a factor of 1,000.

Neither helium nor deuterium could be formed, however, until the temperature following the "big bang" had dropped to about $10^9$ degrees. The time required for this cooling probably did not exceed a few minutes. The calculations assume that the theory of general relativity is valid and that the universe is homogeneous and isotropic.

Peebles suggests that the computed helium abundance could be tested by comparing it with the observed abundance of helium in the oldest stars in our galaxy. Unfortunately the helium abundance of these stars is not known with much certainty. The abundance of helium in the sun, which is a star of a later generation, is believed to lie between 25 and 30 percent by mass. There is reason to believe this much helium could not have been created by the normal stellar conversion of hydrogen to helium in the entire lifetime of the galaxy. This is indirect evidence for a high abundance of helium in the primeval gas.

Peebles points out in conclusion that calculations of helium abundance provide "a remarkably stringent test of general relativity." If the reality of the primordial fireball is confirmed and if the calculated abundance of primeval helium is *not* supported by direct ob-

# Catching up with Computers: A report from General Dynamics

## Getting the facts faster:

Not long ago, weather satellites were transmitting hundreds of millions of bits of infrared data daily. With high-speed computers—and standard plotting techniques—fully processed data became available six months later.

By then the weather had changed.

A utility company found its customers increasingly annoyed at delays in answers to questions about their accounts. Even with its computer, by the time all records were checked, and an individual explanation written and mailed, sometimes weeks had passed.

Today, the infrared cloud cover information is available in map form within a few hours after the satellite has discharged its information. The utility customer can phone his query, get an explanation within one minute.

What has made this possible are *information-display systems* which translate data directly from computers into readily understandable form.

## Shrinking to size:

Computer calculations can be made at speeds measured in billionths of a second. "Answers" can be turned out in millions of computer "words" every hour. But these miles of words must be reduced to manageable size before the "answer" makes any sense.

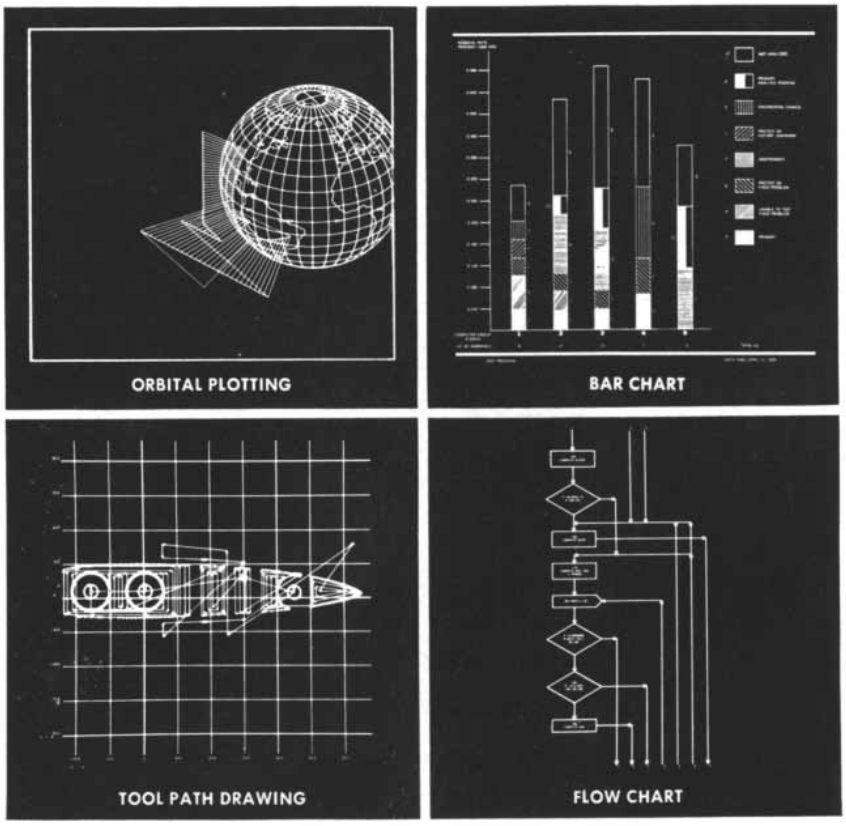
Now at the utility, the operator who receives a query simply punches the customer's account number into a keyboard connected to a central computer. Within one second, the customer's record appears on an information-display screen with a paper copy printed out if desired.

More complex equipment is helping hunt submarines, analyzing the radiation flux in the heart of a nuclear reactor, graphically showing the progress of a Gemini capsule in orbit.

The heart of the display systems produced by General Dynamics, through our Stromberg-Carlson subsidiary, is a specialized cathode ray tube.

Data from a computer are converted to "steer" a stream of electrons through a matrix into which up to 200 different characters have been etched. The beam, focused on one at a time, is shaped as it passes through the matrix. When this shaped beam hits the phosphor-coated face of the tube, the character is reproduced—in some of our displays as fast as 100,000 characters per second.

Equally important is the ability of the system to "draw" on the face of the tube. Each "word" in a computer answer may represent the location of one data point or of a series of points. Short straight lines connecting these points may be drawn in any direction at rates averaging over 10,000 points per second, cumulatively building complex diagrams, even circles perfect to the eye. Drawings once laboriously hand-plotted over days or weeks now often can be completed within one second.




**PICTURES IN A SECOND, DRAWN BY COMPUTER-DISPLAY**

## Instant pictures:

The resulting words and pictures can be viewed directly, photographed on microfilm or printed out to provide immediate diagrams, tables, maps or charts. In fact, the computer-display systems have been used to make animated movies showing the probable behavior of a satellite in orbit and of shock waves in wind tunnel tests.

With company records in a central computer, the sales manager can get a detailed picture of the sales history of a product in any area, or the president, a financial summary—both in simple graphic form and within seconds after requesting the information.

Probably the most dramatic uses are "on-line, real-time" operations—showing what is actually happening at the moment. Consider one system being tested for local air traffic control.

A central computer receives up-to-the-second information on a plane's position, its flight plan, the weather and other conditions. Automatic devices in the plane transmit changes in position. Altitude, direction and speed are computed. The symbol representing the plane appears on the display screen. Next to it are letters and numbers indicating its flight number, altitude, speed and heading.

As the plane moves, its symbol moves across the display panel. As its speed and altitude change, so does the accompanying block of data on the screen. The controller can see at a glance exactly what planes are in his vicinity, their relation to each other and to his station. Possible trouble can be eliminated before it can start.

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**GENERAL DYNAMICS**

servation, "the result will be difficult to explain on the basis of conventional general relativity."

### *Shape Perception in Infants*

It appears that infants have the capacity for "shape constancy," the ability to recognize an object's shape regardless of rotations that change the image of it projected on the retina. The origin of shape constancy has been a matter of controversy among psychologists for many years. First it was assumed that shape constancy was a learned ability, depending on acquaintance with the appearance of specific objects in specific orientations. Gestalt psychologists then suggested that the shape of an object as it is projected on the retina and the orientation of the object in space are detected simultaneously, and that the actual shape of the object is inferred from a correlation of projective shape and orientation. This proposal has not been confirmed in adults and has been hard to test in infants.

T. G. R. Bower of Harvard University devised an "operant conditioning" technique, of the kind first developed at Harvard by B. F. Skinner for pigeons and since applied to many other animals, with which to test shape perception in babies. He trained his subjects, about two months old, to respond to a certain stimulus by turning their heads to the left, and he reinforced correct responses by popping up in front of the infants with a cheery "Peekaboo!" Each baby was trained to respond to a 25-by-50-centimeter wooden rectangle that, instead of being set at a right angle to the infant's line of sight, was rotated 45 degrees and therefore projected a trapezoidal shape on the subject's retina. As Bower reports in *Science*, babies trained in this way responded to the rectangle, whether it was set in the 45-degree orientation or at a right angle to their line of sight, in preference to a trapezoid that cast the same retinal image. This result ruled out the idea that shape constancy is learned.

To test the suggestion that shape constancy depends on the correlation of projective shape and orientation, Bower examined the babies' ability to discriminate among (1) four orientations of the rectangle; (2) four trapezoids that, although presented in the right-angle position, cast the same retinal images as the variously oriented rectangles; (3) four orientations of the rectangle with its edges screened out. Surprisingly, the babies discriminated least well under condition 1, even though it was in that situation that they had both projective shape and orientation as differentiating features. A third experiment confirmed the finding that variations in orientation, and therefore in projective shape, do not seriously interfere with an infant's ability to recognize actual shape.

### *Swift Slum Clearance*

A new approach to the rehabilitation of slum dwellings is being tested in New York. The technique is to cut a shaft through each vertical array of apartments in a tenement, strip most of the insides of the building, remove them through the shaft by means of a crane and lower materials for reconstruction through the shaft. The sponsors hope to reduce the time needed to rehabilitate a tenement to 48 hours and the cost to between $5,000 and $7,000 per apartment, compared with $9,000 to $11,000 for conventional methods and $22,500 for new public housing. By means of the new technique the problem of relocating tenants would be eliminated.

Several organizations have a role in the project. The Institute of Public Administration is coordinating and evaluating the venture with a grant of $390,000 from the U.S. Department of Housing and Urban Development. The Carol W. Haussamen Foundation has bought the three demonstration buildings, is financing their rehabilitation and will operate the rehabilitated apartments on a nonprofit basis. CONRAD Engineers, a New York firm, has developed the "instant rehabilitation" technique.

This project is under way in three neighboring buildings on East Fifth Street. Two of them are empty, one is occupied. The demonstration began in one of the vacant buildings last month. This work will take three or four months because the sponsors are testing the technique and comparing various building materials. The second vacant building will be rehabilitated this summer with the techniques and materials that prove most suitable; the work is scheduled to take about a week. Then the technique will be applied to the occupied building, with the tenants moving out for less than a week.

Once workmen have finished installing new windows, walls, ceilings and floor coverings in a tenement, preassembled kitchen-and-bathroom units will be lowered through the shaft. On each floor this package will close the shaft. When the plumbing and wiring in the packaged units have been con-


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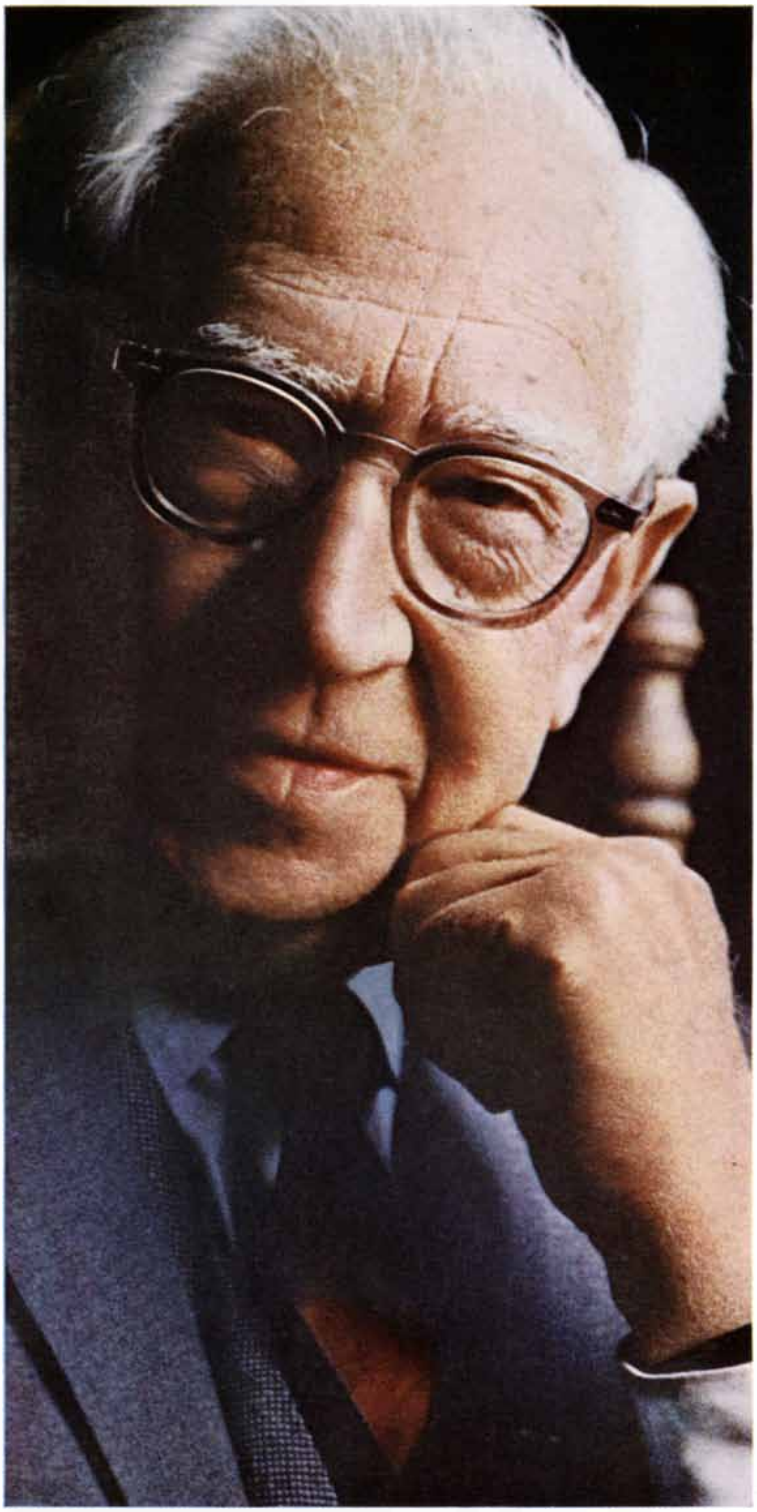
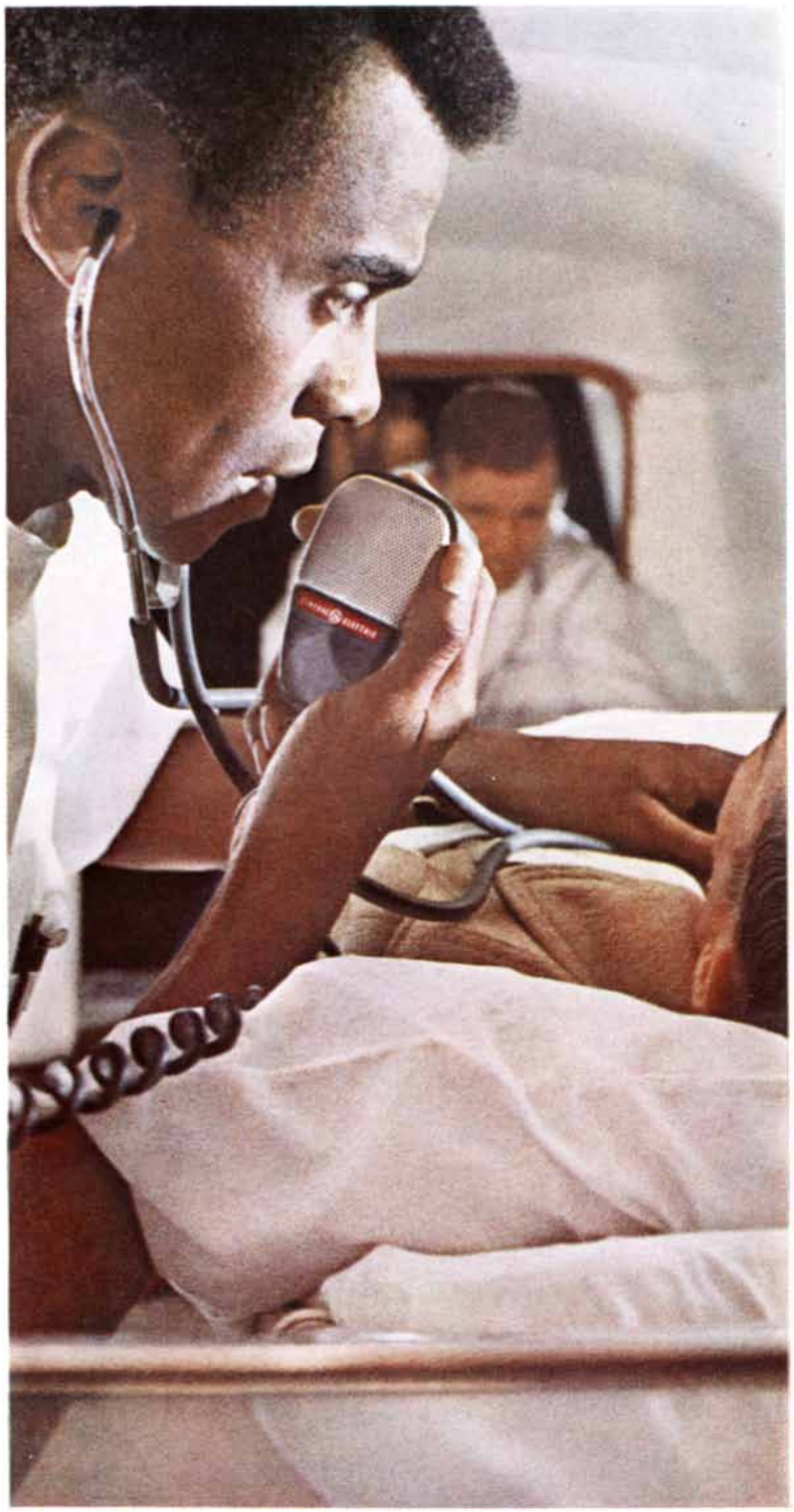


Patients recover faster and live extra years as a result of new intensive care in hospitals. A G-E cardiac monitor, for example, can keep 24-hour watch on heart patients, summon help at least sign of trouble.

# saving minutes when life's at stake?



Ambulance intern with G-E 2-way radio alerts hospital emergency team for critical case. And with pocket FM radio receivers doctors can be paged throughout an entire hospital complex.

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**(and we're trying to make it easier for doctors to perform their miracles)**

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Medical advances in the past 20 years have been greater than in the past 20 centuries. Back of these modern miracles is medicine's increasing use of ideas from many sources of science and engineering. General Electric is one of these sources.

G-E computers, for example, are storing medical knowledge that no human memory could contain. And it can be tapped by doctors in seconds for use in diagnosis and treatment.

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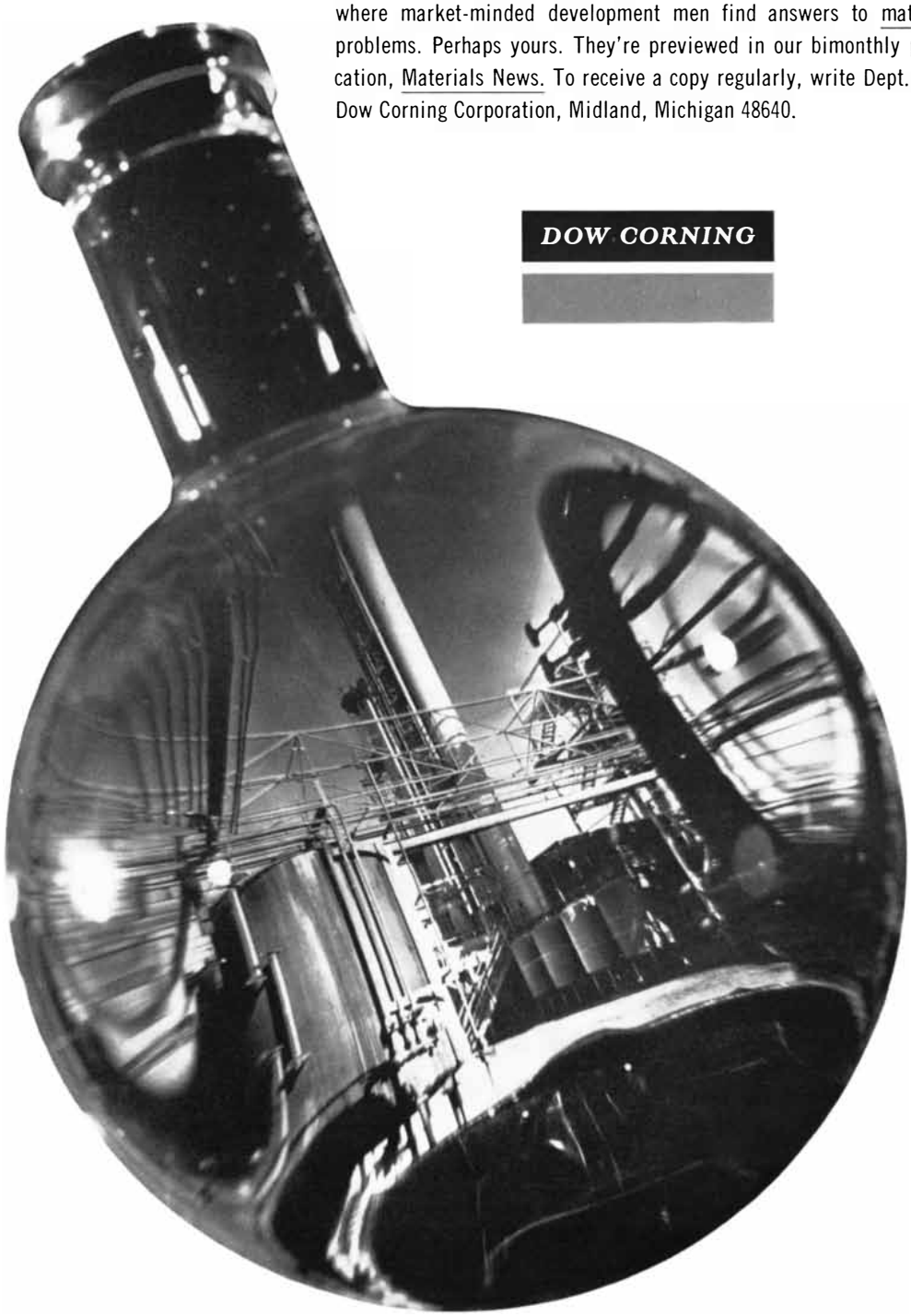

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nected to that of the building, the apartments will be ready for the return of the tenants.

### *Bare Minimum*

The first direct measurement of the minimum energy needed to initiate a chemical reaction has been reported by workers at the California Institute of Technology. They have found that .33 electron volt of energy is required to uncouple the two atoms that constitute a hydrogen molecule and to link one of the freed hydrogen atoms with an atom of deuterium (heavy hydrogen). The experiment was performed by John Michael White, a graduate student, working under the direction of Aron Kuppermann.

To energize the reaction White used a diffraction grating to select light of known wavelength from the output of a mercury-vapor lamp. By changing the orientation of the grating he could change the wavelength. The shorter the wavelength, the higher the energy.

The reaction vessel into which the light was shined contained a mixture of two gases: hydrogen and deuterium iodide (molecules containing one atom of deuterium and one of iodine). The energy of the input photons of light could be adjusted to split the molecules of the deuterium iodide but not the molecules of hydrogen. Some of the deuterium atoms so liberated would collide with hydrogen molecules and split them; a deuterium atom would then combine with one of the unattached hydrogen atoms, forming a molecule of deuterium hydride.

The experiment was performed with light of selected wavelengths and the contents of the reaction vessel were analyzed after each run. In this way it was possible to establish the minimum energy needed to create deuterium hydride. The minimum value was found to be .33 electron volt.

Such experiments should make it possible to assign values for the probability that two colliding atoms or molecules will react. No direct measurement of this probability yet exists. "The measurement," says Kuppermann, "could indicate whether the motion of atoms and molecules undergoing chemical reactions can be described sufficiently well by classical mechanics or whether strong quantum effects are present." This should lead in turn to better predictions of chemical reaction rates—which would be of value in the chemical industry as well as in the research laboratory.

# The Scientific Experiments of Mariner IV

*Concluding a series of three articles on the highly successful voyage of the spacecraft. Its instruments not only provided new information on Mars but also monitored fields and particles in planetary space*

by Richard K. Sloan

The mission of *Mariner IV* was to conduct flyby observations of the planet Mars and to perform field and particle experiments in interplanetary space. The *Mariner IV* spacecraft successfully transported its carefully selected complement of scientific instruments to its target, which was 134 million miles from the earth at the time of encounter, and flew them past the planet at an accurately known distance and with accurately known orientations. The first article in this series recounted the construction and flight of the spacecraft [see "The Voyage of Mariner IV," by J. N. James; SCIENTIFIC AMERICAN, March]; the second article described the results of one of the scientific experiments, the photography of the surface of Mars [see "The Photographs from Mariner IV," by Robert B. Leighton; April].

This concluding article on *Mariner IV* will describe the other experiments carried out by that marvelously successful spacecraft and summarize their main results. The experiments were designed "to provide maximum information about Mars" within the weight limitations imposed by a 575-pound spacecraft. (As the preceding articles have noted, the payload had to be sharply reduced when the Atlas/Centaur launch vehicle had to be replaced by an Atlas/Agena vehicle, which had only about a third of the weight-lifting capacity for interplanetary missions.)

Five of the instruments placed aboard *Mariner IV* sampled the magnetic field and energetic particles in the region between the earth and Mars, as *Mariner II* had previously sampled fields and particles between the earth and Venus [see "The Voyage of Mariner II," by J. N. James; SCIENTIFIC AMERICAN, July, 1963]. A sixth instrument measured the impact of micrometeorites during the voyage. At Mars the magnetic-field and radiation instruments also searched for the planet's magnetic field and determined whether or not Mars was circled by radiation belts similar to the earth's Van Allen belts. In addition the trajectory of *Mariner IV* was selected to carry the spacecraft behind Mars so that radio transmission from the craft to the earth was interrupted for a short period. During this occultation experiment, as it was called, the radio signals passing between *Mariner IV* and the earth grazed the edge of the planet, passing through its atmosphere as the craft disappeared behind Mars and again as it reappeared. By measuring how the signal was distorted during this experiment it was possible to infer important properties of the Martian atmosphere.

The responsibility for the scientific aspects of the mission was spread widely among investigators in Government and academic institutions [*see bottom illustration on page 65*]. It was my good fortune, as project scientist, to work closely with all these men. My job was to see that the requirements of their individual experiments were met within the many constraints imposed by a spacecraft system and the mission.

## The Six Instruments

Because the Mariner was a fully attitude-controlled spacecraft, the six instruments were placed to measure data along known and carefully selected coordinates [*see illustrations on pages 64 and 65*]. The spacecraft was stabilized so that the plane of the four solar panels was perpendicular to the sun and thus the craft's axis was aimed steadily at the sun throughout the flight. The craft was prevented from rolling about this axis by a star-tracking device pointed at Canopus, the second-brightest star in the sky, which is 14 degrees from the south ecliptic pole. This pole is an imaginary point due south of the plane of the earth's orbit. Except for brief periods early in the flight, when *Mariner IV* lost its fix on Canopus, this orientation was maintained with high precision. Here is a brief description of the six instruments.

1. Magnetometer. This instrument was built by the Jet Propulsion Laboratory for a team headed by Edward J. Smith of that laboratory. It employed the physical principle that the presence of magnetic fields will modify the transparency of a plasma of metastable helium ions to infrared radiation whose wavelength is 1.083 microns. The magnetometer basically consists of an infrared source, a helium cell, an infrared detector and a set of coils around the helium cell. The coils produce a rotating magnetic field in the helium, resulting in a synchronous modulation of the infrared intensity sensed by the detector. An external field disturbs the normal detector output signal, producing an error signal that is fed back to the coils as a current sufficient to nullify the external field. A measurement of this current provides the output signal of the magnetometer. The instrument used in *Mariner IV* had a dynamic range of $\pm 360$ gammas and was sensitive to changes of less than one gamma on all three axes. (One gamma equals $10^{-5}$ gauss; the magnetic field of the earth at the Equator is about .5 gauss.) The magnetometer made four measurements every 50.4 seconds.

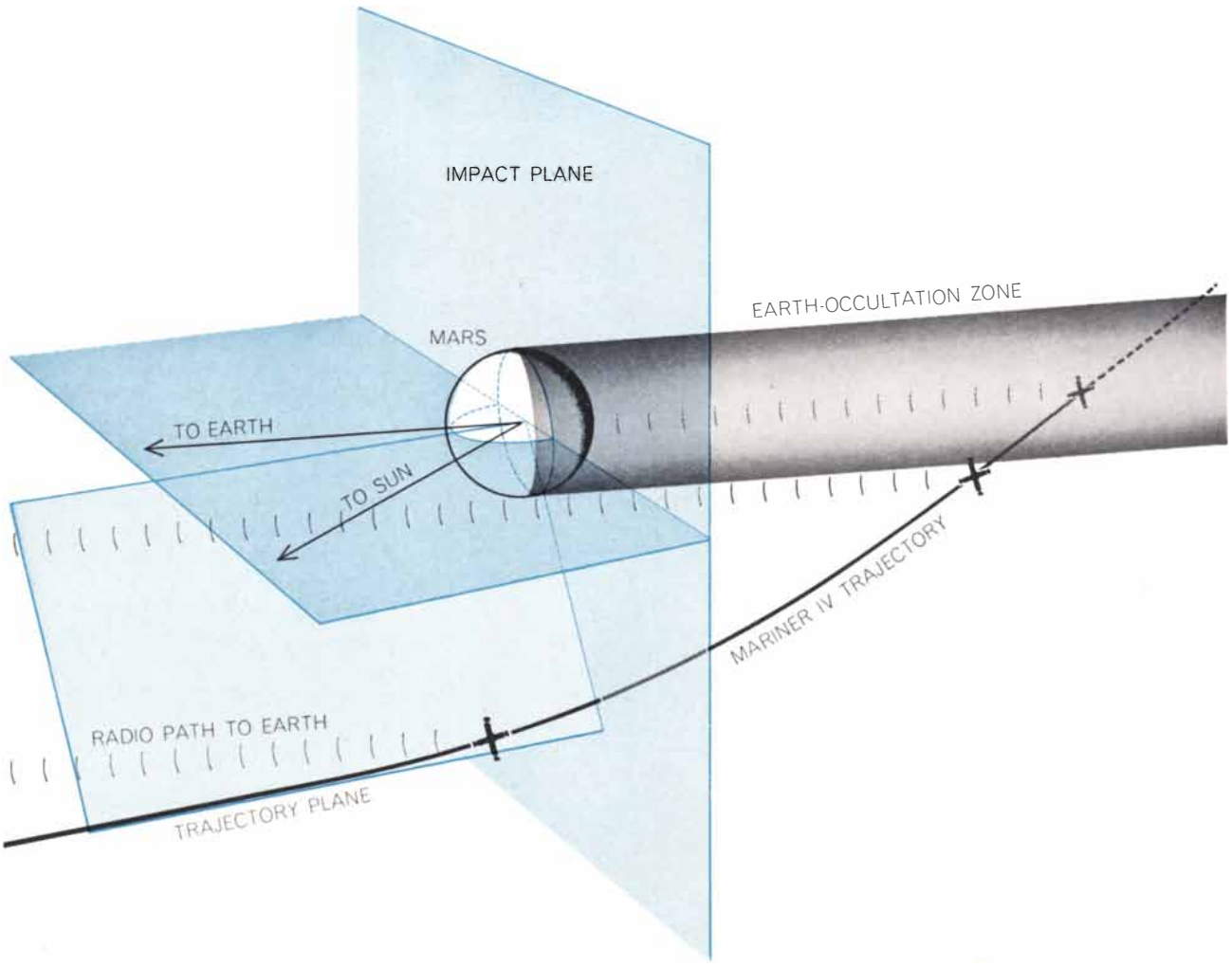
2. Ionization chamber. This device was built by the Jet Propulsion Laboratory for H. Victor Neher of the California Institute of Technology and H. Anderson of the Jet Propulsion Laboratory. It was a duplicate of the instru-

ment that had been flown to the vicinity of Venus by *Mariner II*. Both instruments measured the average total ionization of particles that could penetrate a stainless-steel shell .01 inch thick. To penetrate the shell, electrons had to have energies above .5 million electron volts (mev); protons had to have energies above 10 mev. The chamber itself consisted of a five-inch sphere filled with argon at a pressure of four atmospheres. Particles that passed through the gas would knock electrons out of the atoms. These electric charges were collected and the current was measured. A Geiger tube mounted nearby counted the number of particles. By combining the current measurement with the particle count, much could be deduced concerning the nature of the charged particles that passed through the instrument.

3. Cosmic-dust detector. This instrument was built by a team at the Goddard Space Flight Center headed by W. Merle Alexander. It consisted of a nearly square aluminum plate, 22 centimeters on a side, to which a sensitive microphone was attached. When the plate was struck by a particle of dust, it would vibrate, activating the microphone. The plate was coated on both sides with a thin film of insulating material, over which was deposited a thin film of metal. A voltage was applied between the outer conducting film and the aluminum plate, producing what was in effect a capacitor. When a particle penetrated the metallic outer film and the insulator, it discharged the capacitor and gave rise to a pulse that indicated which side of the plate had been hit.

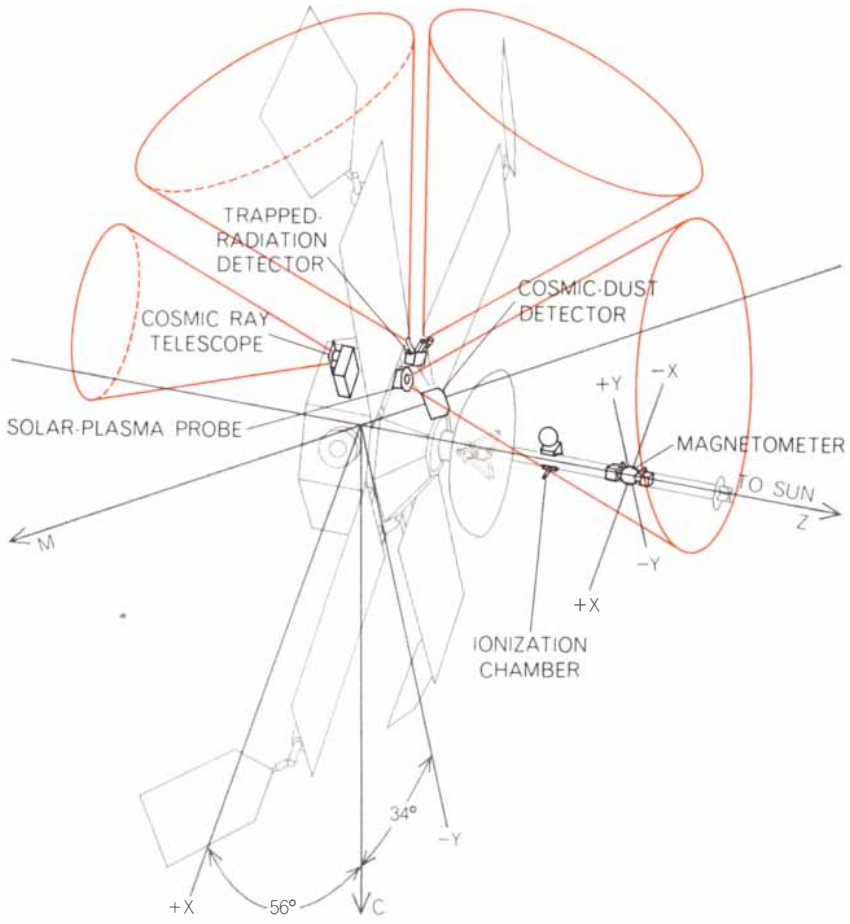
4. Solar-plasma probe. This instrument was built at the Massachusetts Institute of Technology under the supervision of Herbert S. Bridge and is similar to probes carried by the IMP (Interplanetary Monitoring Platform) and Pioneer satellites. The probe was designed to collect protons of the solar wind that had energies between 30 and 10,000 electron volts. An internal program assigned the energy of each proton to one of 32 logarithmically related intervals within the total range. The detector was divided into three equal pie-shaped sectors to provide directional information on the flow of the solar wind.

5. Trapped-radiation detector. So




**OCCULTATION EXPERIMENT provided the climax of *Mariner IV*'s near-perfect mission to the vicinity of Mars. The spacecraft approached from below the planet's orbit and was deflected upward by the planet's gravitational field. The spacecraft's trajectory is plotted here as it would have appeared to an observer on Mars. The Martian observer would see *Mariner IV* sweep under his planet from west to east. This retrograde motion is explained by the fact that at encounter Mars was traveling faster with respect to the sun than was the spacecraft. The "impact plane" is a plane perpendicular to the trajectory of the spacecraft before it was pulled toward Mars by the planet's gravity. About an hour after the time of closest approach the occultation experiment began when *Mariner IV*'s radio beam passed through the thin atmosphere of the planet just before being cut off. Fifty-four minutes later the beam passed through the atmosphere again on the far side of Mars. The experiment showed the atmosphere to be even thinner than expected.**

named because it was designed to measure the particles trapped in the magnetic field of the earth—or of Mars, if it possessed such radiation—this instrument was built at the State University of Iowa under the direction of James A. Van Allen. It consisted of three Geiger tubes and a solid-state detector. The four measuring devices were provided with shielding and electronic circuitry that enabled them to classify the energy of electrons and protons into various ranges above 40,000 electron volts. All together there were five recording channels, each of which reported in rotation the total counts in a 45-second period. The dynamic range was from one count in 10 seconds to more than 50,000 counts per second. Two of the Geiger tubes were shielded so that they counted electrons only if their energies exceeded 40,000 electron volts and protons only if their energies exceeded 500,000 electron volts. The sole difference between the two tubes was that one was pointed at an angle of 70 degrees from the sun, whereas the other was pointed at an angle of 135 degrees from the sun. Both accepted particles that impinged on the tube within an acceptance-cone angle of 60 degrees. The third Geiger tube was shielded to accept electrons with energies above 130,000 electron volts and protons with energies above 3 mev. It was pointed 70 degrees from the sun and had the same acceptance angle as the other tubes. The fourth detector, the solid-state detector, responded to protons with energies between .5 and 11 mev. The fifth recording channel was provided by a discriminator on the solid-state detector that limited its response to protons of .9 to 4 mev.




***MARINER IV*'S INSTRUMENTS** surveyed space in the carefully selected directions shown here. The magnetometer measured magnetic fields along three axes: the *z* axis points toward the sun; the *x* and *y* axes are parallel to the solar vanes. The cosmic-dust detector, which recorded the impacts of micrometeorites, was mounted perpendicularly to the line of flight (*M*). The other four instruments measured energetic particles. The ionization chamber was omnidirectional. The solar-plasma probe was aimed 10 degrees off the *z* axis. The trapped-radiation detector was an assembly of four tubelike instruments with acceptance cones aimed at selected angles away from the sun. The cosmic ray telescope was aimed directly away from the sun. The illustrations on the opposite page provide additional details.

6. Cosmic ray telescope. Similar to instruments previously flown on IMP satellites and to one currently aboard the Pioneer deep-space probe, this device was built under the direction of John A. Simpson of the University of Chicago. The telescope is composed of three solid-state detectors and absorbers placed one above the other to accept incoming particles within a cone angle of 40 degrees. The depth of penetration of a particle and its energy loss in the detectors determines its energy and identifies whether it is a proton, electron or alpha particle. The measurement of these quantities is made by a 128-channel analyzer. The spectra and fluxes of each kind of particle are studied over the energy range from 1 to 170 mev. The cosmic ray telescope was located on the underside of *Mariner IV*, where it was aimed directly away from the sun.

The output of these six instruments was sampled at the rate of 280 "bits" of information every 12.6 seconds during the early part of the flight, when the radio signal to the earth carried 33⅓ bits per second. Later in the flight, when the telemetry rate was reduced to 8⅓ bits per second, the output rate of the six instruments was decreased by three-fourths to give 280 bits every 50.4 seconds. The total "data frame" consisted of 280 bits from the scientific instruments and 140 bits from instruments that provided spacecraft engineering data [*see top illustration on page 70*].

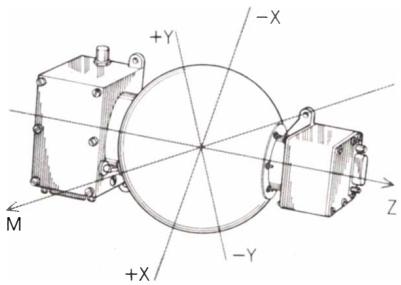
These 420 bits were put into a form suitable for transmission by a central controller called the data-automation system. This system supplied the means for controlling, sampling, synchronizing, "formatting," converting, "buffering" and encoding the data from all instruments. In addition the data-automation system provided a central terminal for the issuance and reception of commands to and from the other subsystems aboard the spacecraft.

## The Data Start to Arrive

The first scientific data from *Mariner IV* were received 45 minutes after launching, when the spacecraft separated from the Agena second stage. All systems operated as expected, providing excellent data on the distribution and intensity of particles and magnetic fields within the earth's magnetosphere. For the first 16⅔ hours of the flight *Mariner IV* was programmed to roll at the rate of about one revolution every 30 minutes. By rotating the spacecraft in the known magnetic field of the earth

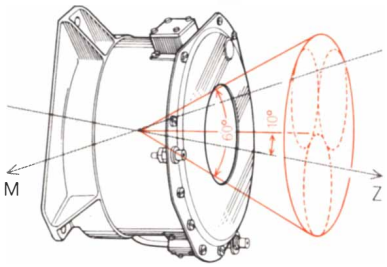
MAGNETOMETER

RANGE: ±360 GAMMAS

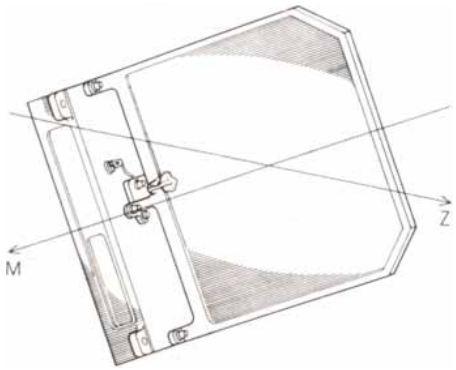



SOLAR-PLASMA PROBE

PROTONS: 30 EV TO 10 KEV

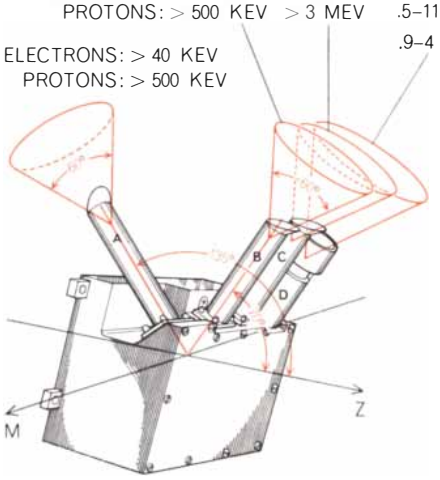



COSMIC-DUST DETECTOR



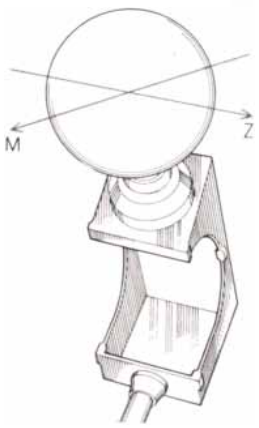

TRAPPED-RADIATION DETECTOR

ELECTRONS: > 40 KEV > 130 KEV NONE
PROTONS: > 500 KEV > 3 MEV .5–11 MEV
.9–4 MEV



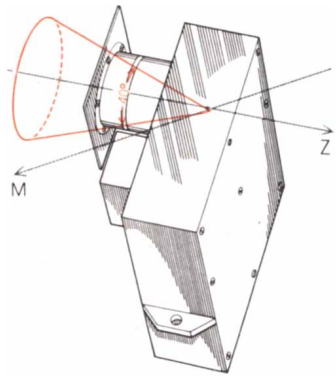

IONIZATION CHAMBER

(OMNIDIRECTIONAL)
ELECTRONS: > .5 MEV
PROTONS: > 10 MEV




COSMIC RAY TELESCOPE

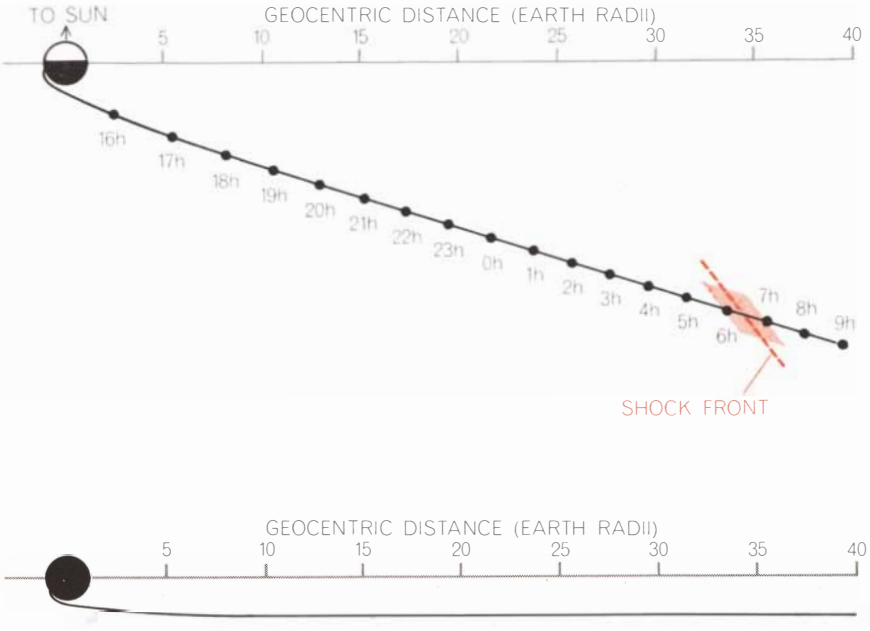
ENERGY RANGE PER PARTICLE:
CHANNEL 1: 1–15 MEV
CHANNEL 2: 15–70 MEV
CHANNEL 3: 70–170 MEV



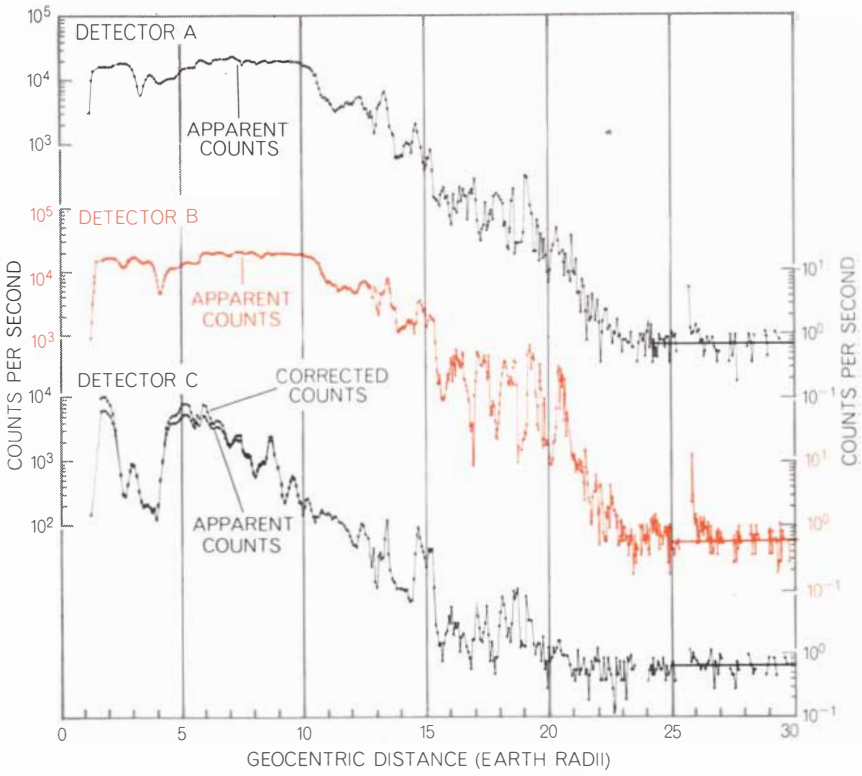

**INSTRUMENT CONFIGURATIONS** and "look" angles are shown as they were oriented during the long voyage of *Mariner IV* to Mars and beyond. The *z* axis is pointed toward the sun; *M* is the direction of flight. The role and operation of the various instruments are described in the text. "Ev" stands for electron volt, "kev" for thousand electron volts and "mev" for million electron volts.

| EXPERIMENT | WEIGHT (POUNDS) | POWER (WATTS) | PURPOSE | PRINCIPAL INVESTIGATOR |
|---|---|---|---|---|
| MAGNETOMETER | 7.50 | 7.30 | Measure magnitude and other characteristics of the planetary and interplanetary magnetic fields | EDWARD J. SMITH<br>Jet Propulsion Laboratory |
| IONIZATION CHAMBER | 2.71 | .46 | Measure charged-particle intensity and distribution in interplanetary space and in the vicinity of the planet | H VICTOR NEHER<br>California Institute of Technology |
| COSMIC-DUST DETECTOR | 2.10 | .20 | Measure momentum distribution, density and direction of cosmic dust | W. MERLE ALEXANDER<br>Goddard Space Flight Center |
| SOLAR-PLASMA PROBE | 6.41 | 2.65 | Measure the very-low-energy charged particle flux from the sun | HERBERT S. BRIDGE<br>Massachusetts Institute of Technology |
| TRAPPED-RADIATION DETECTOR | 2.20 | .35 | Measure intensity and direction of low-energy particles | JAMES A. VAN ALLEN<br>State University of Iowa |
| COSMIC RAY TELESCOPE | 2.58 | .60 | Measure direction and energy spectrum of protons and alpha particles | JOHN A. SIMPSON<br>University of Chicago |
| OCCULTATION | — | — | Obtain data relating to scale height and pressure in the atmosphere of Mars | ARVYDAS KLIORE<br>Jet Propulsion Laboratory |

**SEVEN EXPERIMENTS** were carried out by *Mariner IV* under the direction of the principal investigators listed. An eighth experiment, in which a television camera was used to photograph Mars, was described in last month's issue of SCIENTIFIC AMERICAN.




**OUTBOUND TRAJECTORY of *Mariner IV* carried it through the earth's magnetosphere, which extended to about 23 earth radii along the spacecraft's flight path on November 28, 1964. The magnetosphere is the region in which energetic particles are trapped by the earth's magnetic field. The upper diagram shows the trajectory as seen from directly above the plane of the earth's orbit. The lower diagram is a projection of the trajectory onto a plane perpendicular to the orbital plane. The colored area shows where *Mariner IV* made several passes through the shock front, or boundary, between the magnetopause and interplanetary space. Hours on top trajectory show Universal Time on November 28 and 29.**




**ELECTRONS IN MAGNETOSPHERE produced these data recorded by the trapped-radiation detector. The three traces show the counts registered by the instrument's three Geiger-Müller tubes (*A*, *B*, *C*), whose orientations and response ranges are shown in the illustration at the top of the preceding page. By the time *Mariner IV* traveled out to a distance of 23 earth radii the counts were down to the interplanetary level (*horizontal lines*).**

we were able to correct the magnetometer data for any bias caused by the small remnant field of the spacecraft itself. The roll calibration ensured that later magnetometer data, taken in the very small field of interplanetary space, could be assigned absolute values. In addition the magnetometer data acquired during the programmed role supplied information about the orientation of the spacecraft, which was valuable later when the spaceflight operations staff tried to determine whether the spacecraft was locked on Canopus or on some other star.

The various instruments gathered excellent data on the Van Allen belts and on the magnetic fields associated with these trapped-particle regions of the earth's magnetosphere. The data clearly identified the point where the flux of trapped particles dropped to the level characteristic of interplanetary space and indicated that *Mariner IV* had passed through the shock front, or boundary, between the magnetopause and interplanetary space. Thanks to a fortunate circumstance, *Mariner IV* passed through the shock front several times. After the spacecraft had passed through the shock front once, conditions apparently changed, causing the front to move outward and overtake the spacecraft from the rear. Later *Mariner IV* caught up with the front at its new location and passed through it again. The best data during these interesting encounters were provided by the solar-plasma probe and the magnetometer [*see illustration on opposite page*]. The last evidence of phenomena associated with the earth was detected at a distance of about 39 earth radii (155,000 miles) from the center of the earth, at a point where the sun-earth-spacecraft angle was 112 degrees.

Because *Mariner IV* was moving outward from the sun far beyond the orbit of the earth it provided the first opportunity to investigate whether or not the earth has a long magnetic tail streaming out into space away from the sun. Both theory and certain experimental evidence from terrestrial observations had indicated that there might be such a tail. The best data for establishing the existence of the tail were obtained from the trapped-radiation detector and the magnetometer. A complete analysis of the data, however, failed to reveal any increase in electron density or change in the interplanetary magnetic field that should have been associated with a tail. There is a possibility, of course, that such a tail exists but that it was bent considerably above or below the

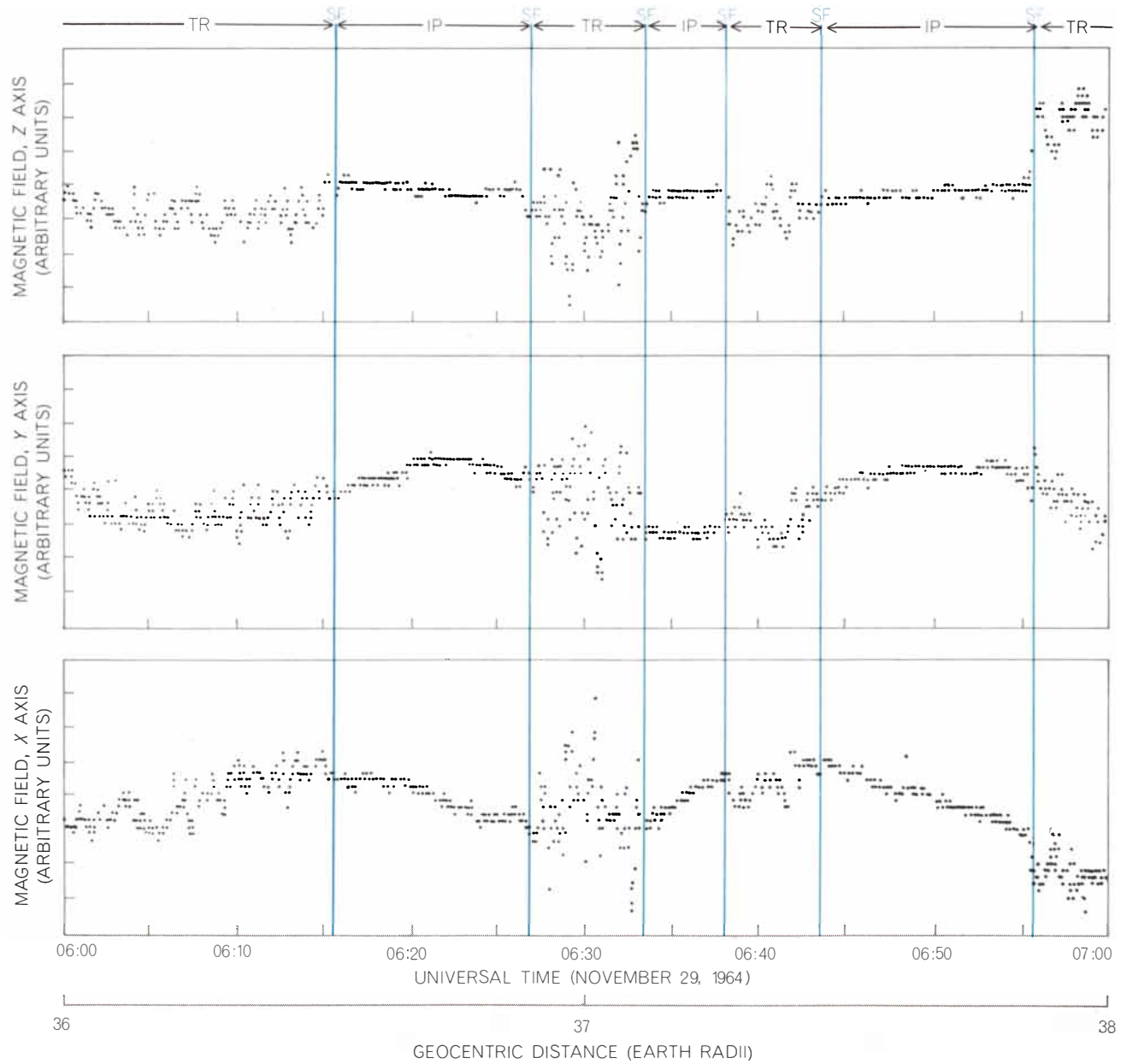
route traversed by *Mariner IV*, which passed behind the earth at a distance of 3,000 earth radii.

Two instrument malfunctions occurred while *Mariner IV* was cruising in interplanetary space. About one week after the launching on November 28, 1964, a resistor in the solar-plasma probe opened. Although the instrument continued to operate, it supplied data in a form that requires very complex and time-consuming analysis. The second instrument failure followed a breakdown of the Geiger tube in the ionization chamber, which eventually caused the ionization chamber to stop functioning. The breakdown was apparently initiated by a solar flare that occurred in early February, 1965.

## A Report on Interplanetary Space

Probably the most significant overall result from the interplanetary flight of *Mariner IV* is the general confirmation that conditions in space in 1965 were similar to those in 1962 when *Mariner II* made its flight to Venus. This is consistent with the fact that both flights took place during a period of low solar activity. Because *Mariner IV*'s instruments were generally more sensitive and discriminating than the instruments aboard *Mariner II*, they provided more detailed information about the solar phenomena observed over a seven-month period. In all, 24 solar events were noted, some of them correlated with phenomena observed either on the sun (for example solar flares) or at the earth (changes in magnetic conditions).

Late in the flight several unusual events occurred in which the increased activity took the form of an increase in the flux of electrons only, without the



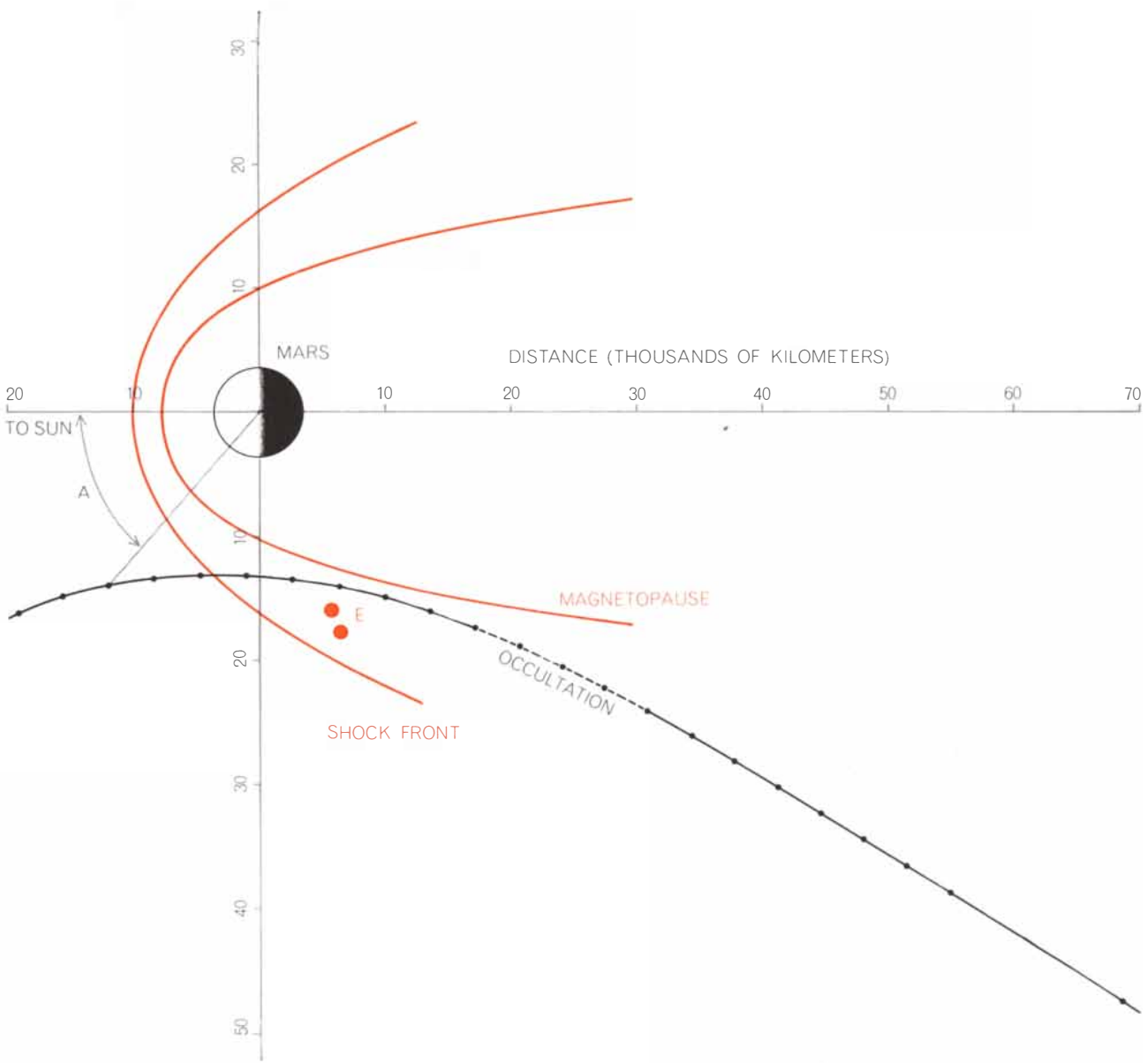

**SIX SHOCK FRONTS (*color*) were recorded by the magnetometer aboard *Mariner IV* when the spacecraft was between 36 and 38 earth radii away from the earth. At about 6:16 Universal Time, November 29, 1964, *Mariner IV* passed from the transition region (*TR*), through the first shock front (*SF*) and into the interplanetary region (*IP*). About 11 minutes later the shock apparently moved outward and overtook the spacecraft from behind. At about 6:33 the craft again passed through the shock front and into interplanetary space, only to be overtaken again about five minutes later. This odd sequence of events was evidently repeated once more.**

expected increase in protons. So far there is no satisfactory hypothesis to explain these unexpected events.

Comparison of the measurements from the cosmic ray telescope with simultaneous measurements from similar University of Chicago instruments in earth orbit on IMP satellites have provided new information on the spatial variation of galactic cosmic ray intensity. In addition the simultaneous observation of several solar events showed that solar particles are strongly guided by the interplanetary magnetic-field lines and that these particles are sometimes stored and carried around the sun within magnetic-field structures rooted in the sun.

Data from the magnetometer were again very similar to those received from *Mariner II*. Apparently because the sun in late 1964 and in the first half of 1965 was slightly quieter than in 1962, the fluctuations in the interplanetary magnetic field were not quite as large as the fluctuations observed during the Venus trip. The average magnetic vector pointed away from the sun at an angle of about 45 degrees and nearly parallel to the plane of the ecliptic. Several times *Mariner IV* recorded abrupt jumps in the magnetic field coincident with the arrival of plasma thrown out by solar flares. On one occasion the increase reached 35 gammas, or more than seven times the typical average daily value.

We particularly wanted to learn how the cosmic-dust recordings of *Mariner IV* might differ from those of *Mariner II*. Out to about 1.2 astronomical units (1.2 times the mean distance from the center of the sun to the center of the earth) the flux of dust recorded by *Mariner IV* was almost identical with the flux *Mariner II* had recorded in traveling from the earth to .72 astronomical unit. Beyond 1.2 astronomical



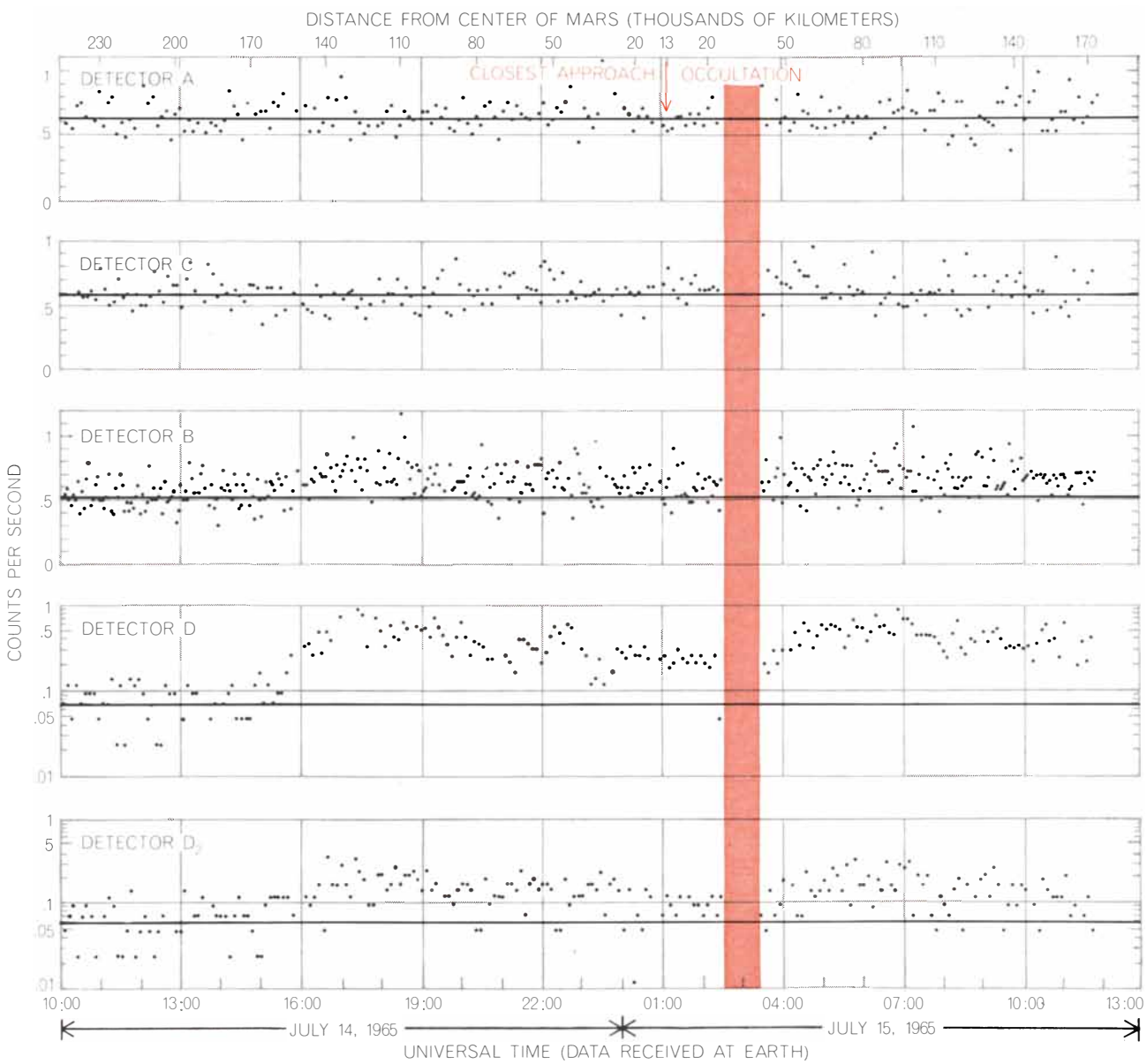

**ENCOUNTER GEOMETRY** is a special polar projection prepared by James A. Van Allen and his associates to show where *Mariner IV* would have passed in relation to a hypothetical magnetopause and shock front, assuming that Mars had a magnetic field one-thousandth as strong as the earth's. The projection correlates *Mariner IV*'s distance from Mars with changes in the angle (*A*) formed between the sun and the spacecraft as measured from the center of Mars. The black dots on the trajectory are at 15-minute intervals. The colored dots (*E*) identify points where electron intensities should match those found at 23 and 25.7 earth radii from the earth, assuming again that the Martian magnetic field is one-thousandth that of the earth. The failure of *Mariner IV* to detect electrons of that intensity suggests that the Martian magnetic field is weaker than the earth's by a factor of more than 1,000.

units the flux increased more or less steadily, reaching a maximum at 1.38 astronomical units, which corresponds to the near point of Mars's orbit to the sun. The decline in flux beyond that distance suggests that some of the dust once present has been swept up by the planet. The cosmic-dust detector showed no statistically significant evidence of any well-defined streams of dust particles.

## The Encounter

The climax of the mission came on July 14 and 15, 1965, when *Mariner IV* reached its target and began sending back to earth data that would settle a number of fascinating questions. Does Mars have a magnetic field? Does it have Van Allen belts? How dense is its atmosphere?

Theorists had predicted that the strength of the Martian magnetic field was probably quite small, no stronger than a tenth of that of the earth. The prediction was based on the planet's mass and rate of rotation. The mass of Mars is about a tenth of the mass of the earth; Mars's rate of rotation is virtually the same as the earth's. Prior to the voyage of *Mariner IV* there had been a single earth-based observation indicating that Mars might have a remarkably strong magnetic field. This was a radio-telescope measurement showing a large output of synchrotron radiation from Mars; this is a form of electromagnetic radiation emitted when charged particles circle around magnetic lines of force. The measurement suggested that Mars possessed belts of magnetically trapped radiation more intense than the earth's Van Allen belts. Although this was an isolated (and admittedly marginal) observation, it gave the Mariner team cause for concern. Tests on several spacecraft subsystems had shown




**TRAPPED RADIATION AT MARS produced these counting rates in the trapped-radiation detector of *Mariner IV*. The spacecraft's distance from Mars at various times can be judged with the help of the illustration on the opposite page. The dark horizontal lines associated with each set of readings represent the background counting rates in interplanetary space. During encounter the rates registered by detectors *A* and *C* showed no change. The slight increase recorded by the *B* detector and the two channels of the *D* detector begins at about 160,000 kilometers from the center of Mars, much too far to be associated with the planet's magnetosphere. Also the particles were protons rather than the electrons one might expect to find trapped near a planet. Van Allen and his associates have concluded that the detectors just happened to pass through protons from a solar event at the time of the encounter.**

**PRINT-OUT OF DATA from *Mariner IV* looked like this as received at the Jet Propulsion Laboratory. Each "data frame" contained 280 "bits" of information (*color*) from the six scientific instruments aboard the spacecraft and 140 bits (*black*) from instruments that provided spacecraft engineering data. Early in the flight the six instruments were sampled once every 12.6 seconds; later, when the transmission rate was reduced by 75 percent, the output of the six instruments was sampled once every 50.4 seconds.**

that it would be impossible to operate a spacecraft properly in trapped-radiation belts 100 times more intense than those surrounding the earth.

Each Mariner experimenter was asked to predict at what distance from Mars his particular instrument would detect the effect of a Martian magnetic field, assuming various values for the strength of the field. If the field were strong, all instruments would show an effect several hours before encounter. If the field were weak, the instruments would reach their most sensitive point shortly after closest approach and just before occultation of the radio signal as the spacecraft went behind the planet.

Throughout the day of encounter, July 15, the eyes of all the experimenters closely followed the plotted output of their instruments as *Mariner IV* sped closer and closer to its rendezvous. The slightest fluctuation was examined. By the end of the day there was a general feeling of disappointment; it was obvious that the planet had produced no effect on either the magnetometer or the instruments recording charged particles. Although this outcome was somewhat unsatisfying, it was nearly as important a contribution to knowledge as a result that might have shown the existence of a magnetic field.

The upper limit for the strength of the Martian magnetic field can be presented in terms of the sensitivity of each pertinent experiment. The trapped-radiation detector and the solar-plasma probe indicated that the strength of the Martian field was less than a thousandth that of the earth, and probably less than a two-thousandth. The cosmic ray telescope also gave an upper limit of a thousandth and the magnetometer—which made a direct measurement of the magnetic field—indicated an upper limit of three ten-thousandths.

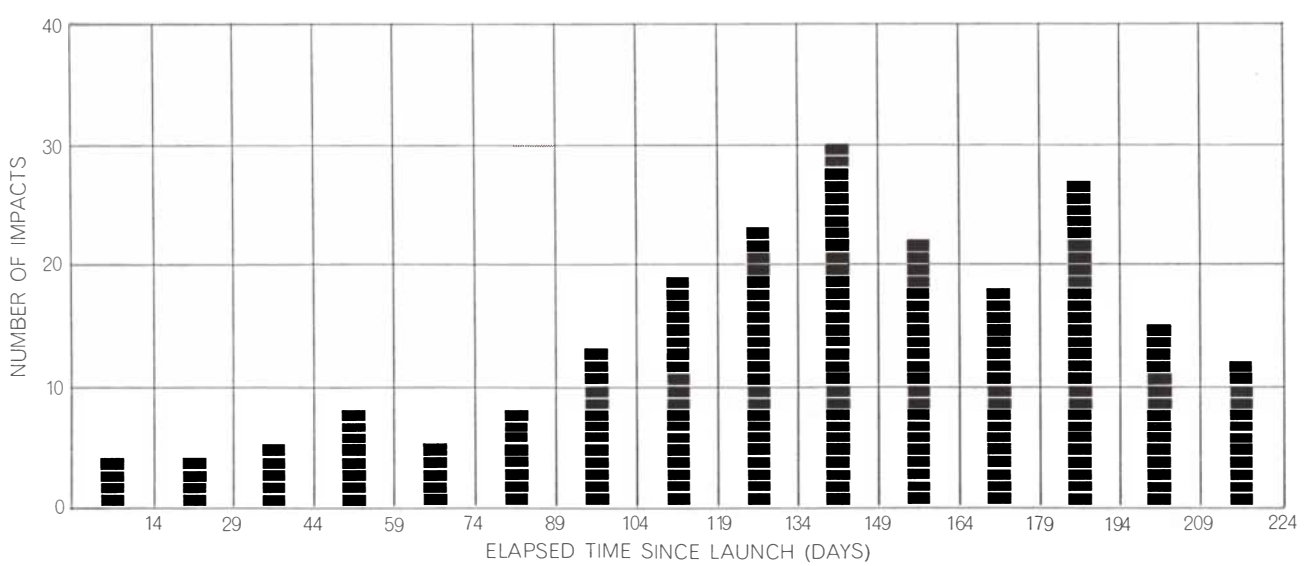
The immediate implication of these results is that without a magnetic field to trap energetic particles Mars is directly exposed to bombardment by cosmic rays and solar plasma. In addition the absence of a magnetic field implies that some feature of the earth's internal structure is lacking in Mars; the missing feature is presumably a liquid core. Without such a core Mars would presumably also lack much of the internal activity that on the earth results in mountain-building and other changes in topography. The photographs taken by *Mariner IV* seem to show a surface that has indeed been little altered over hundreds of millions of years, except for the impact of the objects that produced craters.

## The Occultation Experiment

The Mariner spacecraft had been built and the mission objectives had been defined before the occultation experiment came up for consideration in the spring of 1964. Even then the impetus for including the experiment came from the extreme importance of learning more about the atmosphere of Mars, so that engineers already at work on the Voyager missions of the early 1970's would know how to land a capsule on the Martian surface.

The occultation experiment was so simple that no changes had to be made in the spacecraft. The only new requirement was a slight shift in the aiming point to ensure that the spacecraft would go behind the planet as viewed from the earth, thus requiring that the radio signal pass through the atmosphere of Mars as it was occulted and as it emerged from occultation.

Prior to *Mariner IV*'s flight, knowledge of the Martian atmosphere had



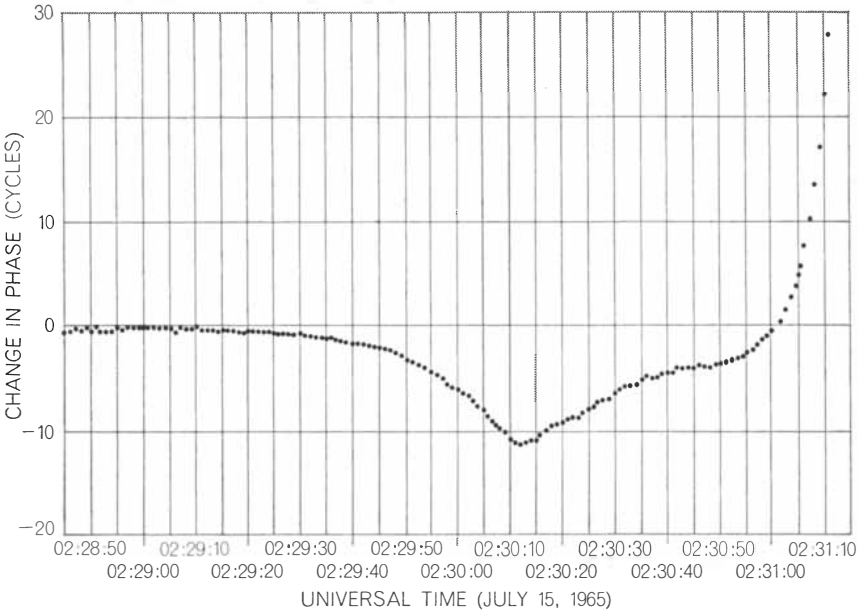

**MICROMETEORITE RECORD shows the number of impacts registered by the cosmic-dust detector in successive 15-day intervals. The first day of flight is not included. The peak period, about two hits per day, was recorded when *Mariner IV* reached the near point of Mars's orbit around the sun. Beyond that point the planet itself may have played the role of a cosmic dust collector.**

been evolving slowly but continually. For some years the accepted value for the atmospheric pressure at the surface of Mars had been 85 millibars, compared with 1,000 millibars for the pressure at the surface of the earth. More recently a careful review of spectroscopic data of carbon dioxide had indicated that the pressure was actually a good deal lower than 85 millibars and probably lay somewhere between 10 and 40 millibars. Even these new estimates, however, involved uncertainties too large to permit efficient design planning for the Voyager missions.

The basic idea of the occultation experiment is straightforward. As the radio signal goes through the atmosphere of Mars it is refracted, and this in turn gives rise to a change in the apparent motion of the spacecraft. If all other effects that produce an apparent motion of the spacecraft are accounted for—such as the actual motion of the spacecraft, the motions of receiving stations on the rotating earth, the lengthening of the transit time of the signal, the refractivity of the earth's lower atmosphere and so on—the remaining unexplained changes in radio frequency can be attributed to refraction by the atmosphere of Mars. For a successful experiment the total change in frequency or phase of the radio signal due to all causes other than passage through the Martian atmosphere must be accounted for to an accuracy of at least one part in 100 billion.

At the point where the signal entered the Martian atmosphere it was early afternoon according to Mars local time, and the sun was only about 20 degrees above the horizon. When *Mariner IV* emerged from behind the planet and the signal again passed through the Martian atmosphere, it passed tangent to a point where, according to Mars local time, it was close to midnight. At the beginning of occultation, as the signal passed through the electrified Martian ionosphere, the signal phase changed about 10 cycles from the expected value. As the signal began passing through the neutral lower atmosphere, its phase began to return to the expected value and then moved in the opposite direction until it reached a value about 25 cycles from the predicted value in the absence of an atmosphere, when the signal abruptly ended [*see illustration on next page*].

The results of the occultation experiment exceeded our expectations. Subsequent analysis has provided accurate values for the critical characteristics of the Martian atmosphere, namely




**OCCULTATION DATA were received in the brief period of about 100 seconds. The results are plotted here as a shift in phase of *Mariner IV*'s radio signal. The shift caused by the electrically charged ionosphere of Mars is becoming apparent at 02:29:20 (Universal Time). Beginning at 02:31:00 the neutral atmosphere begins to contribute the major effect, pushing the phase change sharply in the other direction just before the signal disappears.**

the presence and intensity of the ionosphere, the surface pressure and the scale height. ("Scale height" is a term used to designate the height of atmosphere needed to produce a given surface pressure if the density of the atmosphere were constant from top to bottom. For the earth's atmosphere the scale height is seven kilometers.)

For the electrically neutral part of the Martian atmosphere the best curve through the data yields a model atmosphere with a surface refractivity of 3.7 "N" units and a scale height of nine kilometers. (The refractivity of the neutral part of the earth's atmosphere is 350 N units.) In this model it is assumed that the atmospheric density falls off exponentially with altitude.

The data indicate that there is no obvious change of scale height with altitude up to at least 30 kilometers. This finding, together with terrestrial observations of carbon dioxide in the atmosphere of Mars, makes it fairly certain that the atmosphere consists primarily of carbon dioxide. On this assumption the surface pressure and temperature can be deduced. The surface pressure for a pure carbon dioxide atmosphere would lie in a range between 4.1 and 5.7 millibars and the temperature would be 180 degrees Kelvin (degrees centigrade above absolute zero). For an atmosphere that is 80 percent carbon dioxide and 20 percent heavier gases (argon and nitrogen), the surface pressure would lie between 4.1 and 6.2 millibars. An atmosphere in which carbon dioxide and argon are present in equal amounts would produce a surface pressure of five to seven millibars.

The data on the ionosphere show a distinct ionized layer with a peak electron density of about $10^5$ electrons per cubic centimeter at an altitude of about 125 kilometers. (The peak electron density of the earth's ionosphere is about $10^6$ electrons per cubic centimeter.) The electron scale height of the ionosphere above the electron peak at 125 kilometers is some 25 kilometers. The low altitude of the peak and the small scale height of the ionosphere above it indicate that the temperature of the Martian atmosphere is considerably lower than had been anticipated.

All the foregoing is deduced from the data received at the beginning of occultation, when the signal was passing through the sunlit half of the atmosphere. Preliminary analysis of the data received at the end of occultation on the night side of the planet indicates no detectable ionosphere. The electron density in the nighttime atmosphere is at least 20 times lower than it is in the daytime atmosphere. Because Mars has no magnetic field to complicate the behavior of charged particles in its ionosphere, studies of this region should help in sorting out and understanding various phenomena in the ionosphere of the earth. The fact that the *Mariner IV* signal sampled a complete traverse of the Martian atmosphere from the upper ionosphere to the neutral surface is of inestimable value in understanding that atmosphere as well as that of the earth.

## Trajectory Analyses

The final scientific result to date from the *Mariner IV* mission involves analysis of the spacecraft's trajectory at the time of encounter. The analysis should ultimately provide the best estimate yet of the mass of Mars. A preliminary analysis indicates that the ratio expressing the mass of the sun to the mass of Mars is equal to $3{,}098{,}000 \pm 3{,}000$. (The previously accepted values ranged from 3,110,000 to 3,080,000.) Further computations should also provide an improved value for the mass of the earth-moon system, an improved value for the distance between the earth and the sun (that is, the astronomical unit) and increased accuracy in the ephemeris of Mars (the position of Mars in its orbit at any given time).

At the present time *Mariner IV* is completing a pass behind the sun, offering the opportunity for a solar occultation experiment, provided that a large new antenna is able to detect the spacecraft's faint signal. If the experiment can be performed, it should yield new knowledge about the sun's corona and provide a new measurement of the degree to which the sun's gravitational field bends electromagnetic radiation. The latter experiment is similar to that of measuring the bending of starlight as it passes close to the sun, which has provided one of the well-known tests of the general theory of relativity.

Still later, in the middle of 1967, *Mariner IV* will again come close enough to the earth so that its telemetry signal can be clearly recorded. Should all be well *Mariner IV* will again provide good data on interplanetary phenomena at a period of increased solar activity.

This, then, is a brief summary of the scientific results of the *Mariner IV* mission to Mars. The understanding that the project's engineers and scientists developed of each other's problems culminated in a mission in which nearly every experiment provided optimum results. It is appropriate for me, as a representative of all the scientific experimenters, to congratulate those who designed and built such a beautifully performing spacecraft. *Mariner IV* provided the sure base that was indispensable for producing telemetered data that were free of ambiguity and that could be interpreted with confidence.

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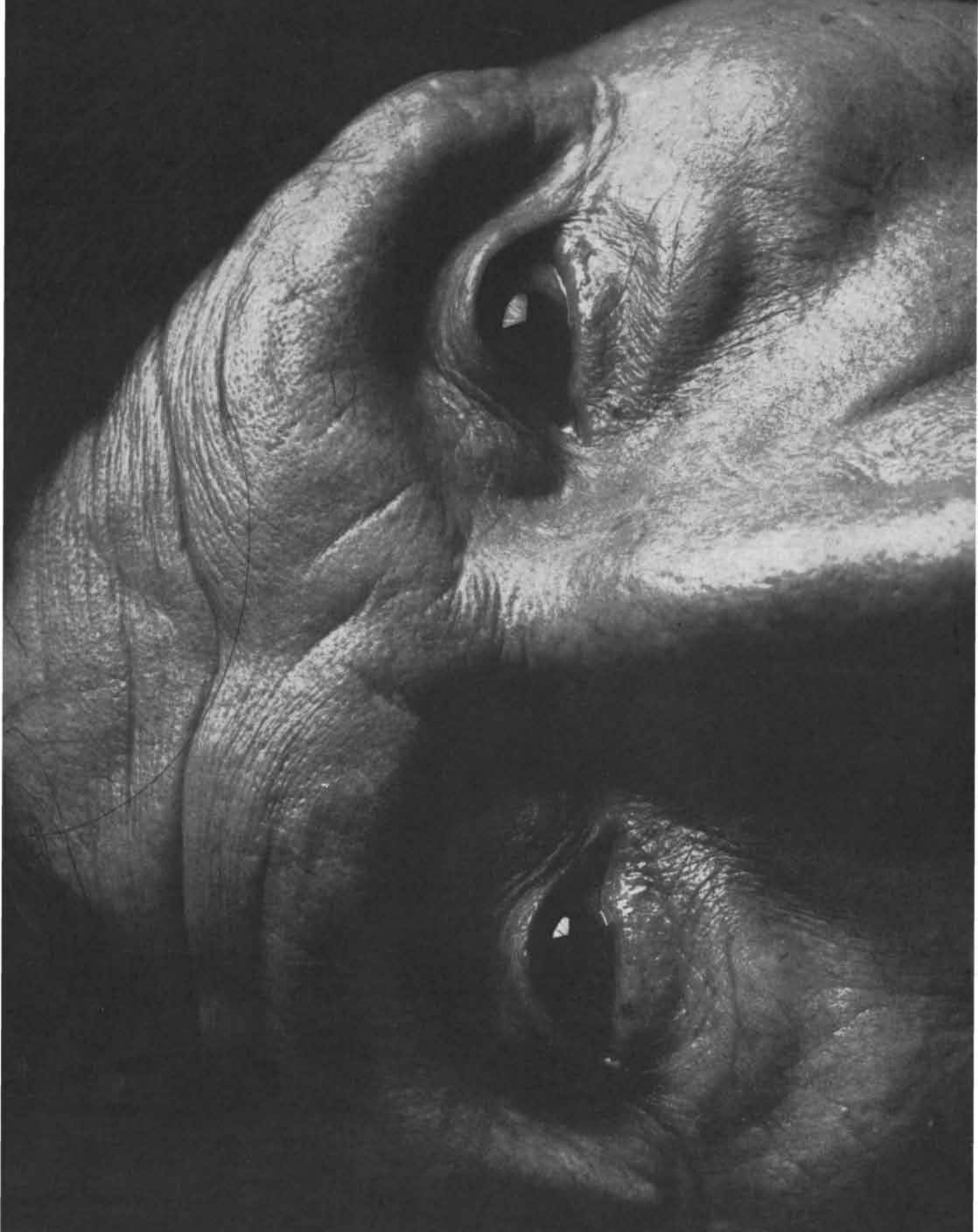

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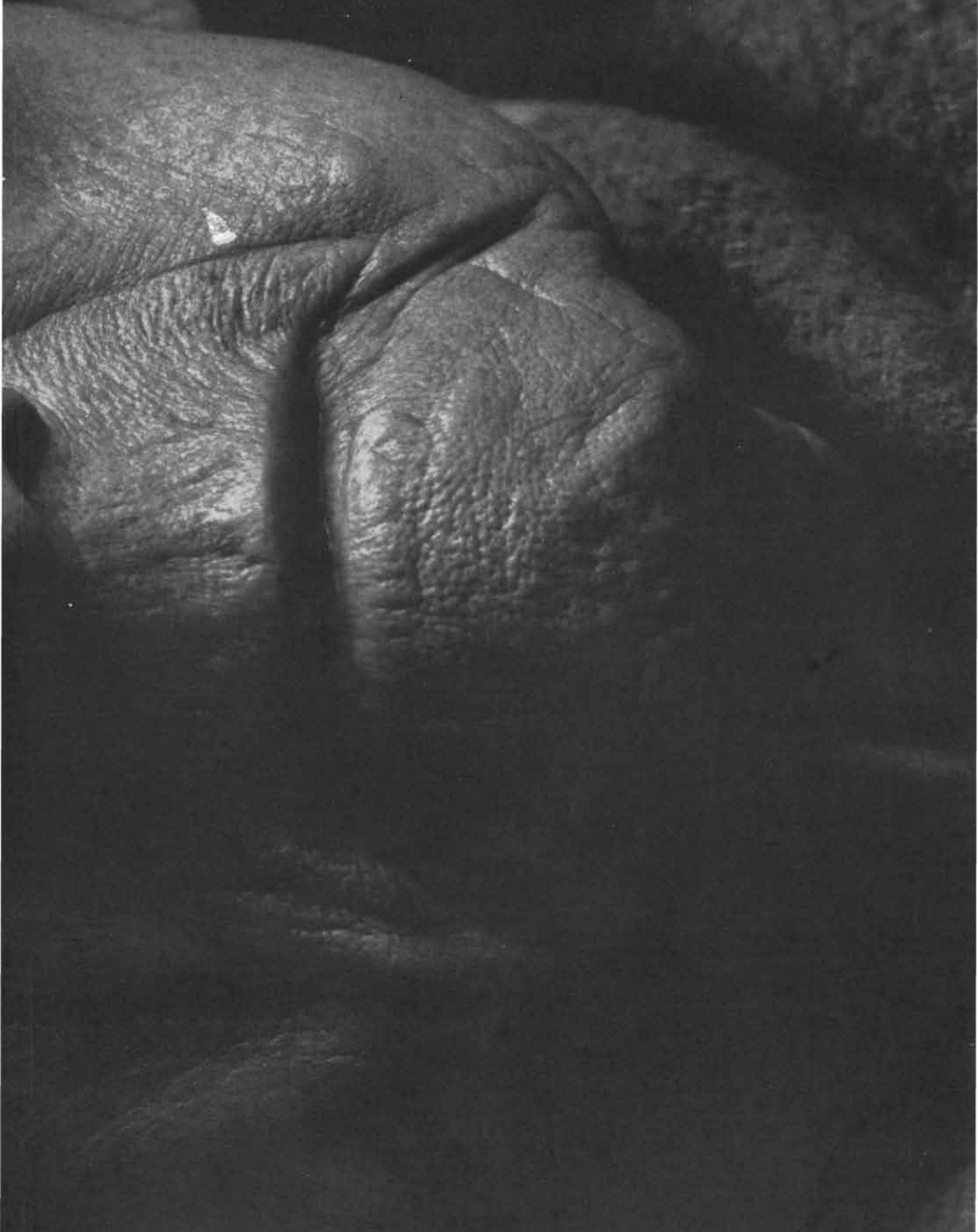

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# How a Tadpole Becomes a Frog

*The dramatic changes of the process are stimulated by thyroid hormone. The level of hormone is regulated by a feedback system involving the hypothalamus of the brain and the pituitary gland*

by William Etkin

Of all the mysteries of life one of the most intriguing is animal metamorphosis. The transformation of a caterpillar into a butterfly or of a tadpole into a frog has long fascinated naturalists, and it is currently yielding important information on various phenomena from evolutionary adaptation to the differentiation and specialization of cells. A recent article in *Scientific American* discussed chemical aspects of the transformation process [see "The Chemistry of Amphibian Metamorphosis," by Earl Frieden; November, 1963]. The present article is an account of what has been learned about the hormonal mechanism that activates the chemical changes that transform a tadpole into a frog.

The frog starts life as a small swimming organism capable only of a fishlike mode of life in the water. It breathes by means of gills, feeds on water plants and pond debris and is equipped with swimming apparatus in the form of a long tail. The duration of the tadpole stage varies greatly: in some of the smaller species it lasts only two or three weeks and the tadpole grows to no more than an inch in length; in the case of the bullfrog the animal remains a tadpole for three years and reaches a length of up to nine inches.

The first sign of change comes when buds near the rear end of the animal's trunk begin to develop into limbs: the jumping legs of the frog. The development of these legs, accompanied by other, less conspicuous changes, takes two to six weeks, depending on the size of the tadpole. In this phase, called prometamorphosis, the animal remains a water-dweller. When the hind legs have grown to about the size of the animal's torso, the tadpole abruptly enters the stage of rapid changes called the metamorphic climax. Forelegs suddenly erupt through small openings in the covering of the gills; the mouth widens and develops powerful jaws and a large tongue; the lungs and skin complete their transformation; nostrils and a mechanism for pumping air develop, and the gills and tail are resorbed by a process of self-digestion and thus disappear. Before the week of climax is over the animal emerges to a new life on land.

The process takes place in an orderly fashion and with exquisite timing, each new development fitting into a complex and perfectly coordinated pattern. The resorption of the swimming tail does not begin until the jumping legs have nearly completed their growth; the nostrils and air-pumping mechanism develop before the gills are resorbed. Clearly the metamorphic process as a whole must be organized by some master mechanism within the animal's regulatory system. The search for the nature of this mechanism has been pursued for more than half a century.

Our story begins with a discovery in 1912 by the German biologist Friedrich Gudernatsch. He fed extracts from various body organs to tadpoles and found that an extract from the thyroid gland had a striking effect. Within a week the treated tadpoles showed some of the typical signs of metamorphosis: rapid growth of legs, widening of the mouth, resorption of the tail. Biochemists eventually identified the thyroid substances that produced these changes as the hormone thyroxine and its three-iodine variant triiodothyronine.

The discovery that thyroid hormones played a critical part in producing metamorphosis raised more questions than it answered. How could this single stimulus generate the entire orderly sequence of metamorphic change, affecting so many body tissues in so many different ways? This question particularly intrigued me when I first became interested in the investigation of metamorphosis more than 30 years ago.

One point seemed obvious: In all likelihood the progress of metamorphosis was connected with increasing activity of the thyroid. Microscopic examination of the gland supported this idea. In tadpoles that had not yet begun to metamorphose, the thyroid was small and its cells appeared inactive. During prometamorphosis, however, the gland grew rapidly, and by the time the animal reached metamorphic climax the thyroid was large and apparently extremely active. Further confirmation of a connection between the level of thyroid hormone and the metamorphic process was provided by experiments in which tadpoles were deprived of their thyroids by surgery and were then given various doses of thyroxine.

Exposing the animals to a low dose of the hormone produced the characteristic development of the prometamorphic stage, marked by rapid growth of the hind legs. If the hormone concentration was maintained at this low level, the later stages of metamorphosis developed only with extreme slowness. High levels of hormone, on the other hand, produced a normal rate of change for such climax events as tail resorption but did not allow enough time for other changes, such as hind-leg growth. The resulting animal was not viable; it could live neither in water nor on land. I found that to induce the normal speed and timing of metamorphosis the hormone concentration had to be started at a low level and then be increased at least twentyfold as the metamorphic

process advanced to the final stage [*see illustrations on next page*].

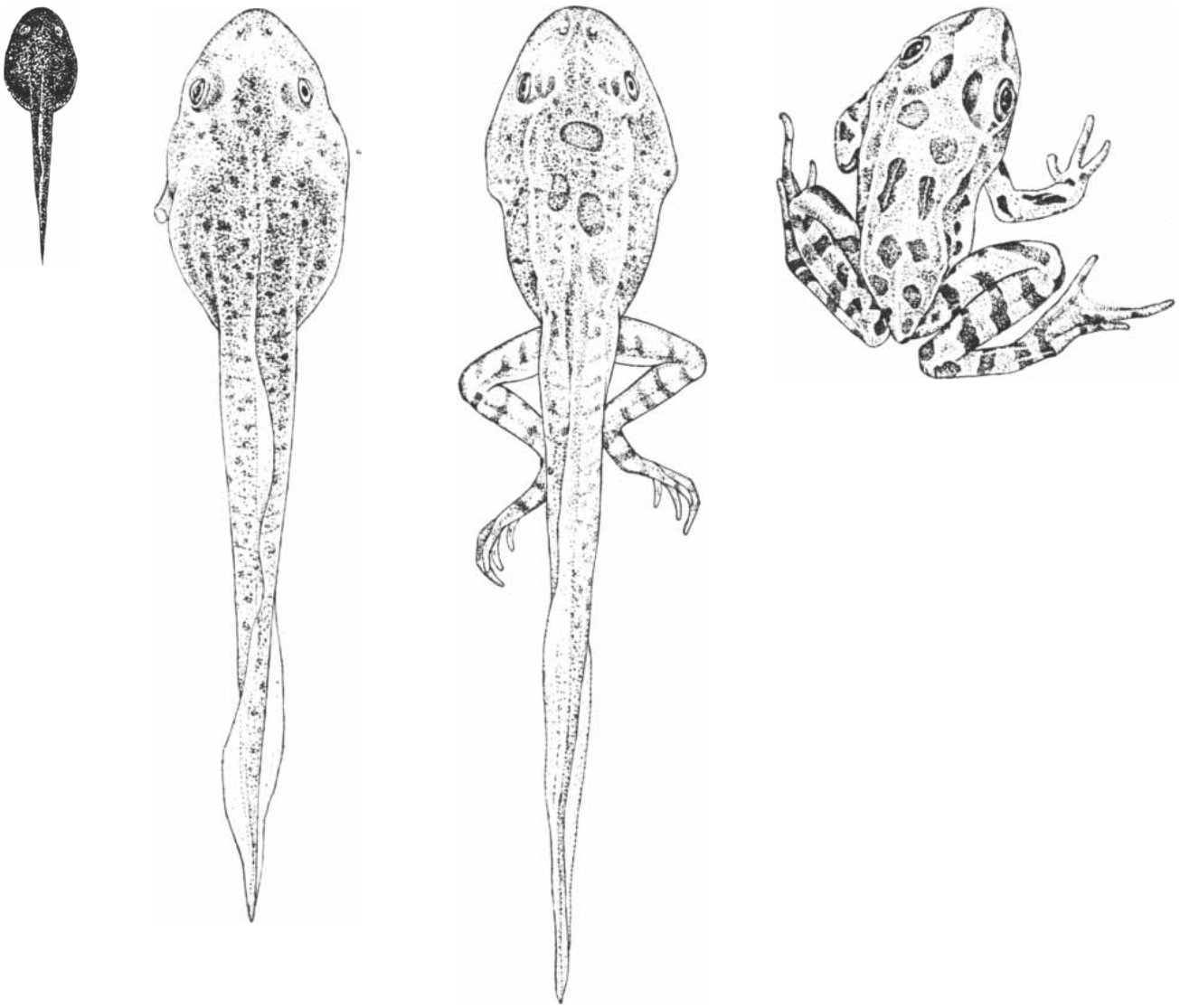
In our laboratory at the Albert Einstein College of Medicine in New York we have developed a standard procedure for transforming immature tadpoles into frogs. We provide the hormone through the water medium in which the animals swim. We start with a concentration of one to three parts of thyroxine to a billion parts of water. When the growth of the tadpoles' hind legs, signaling prometamorphosis, has reached about a third of the normal length, we raise the thyroxine concentration to about 10 parts per billion. Finally, when the forelegs emerge, marking the start of metamorphic climax, we increase the thyroxine concentration to between 200 and 1,000 parts per billion. At this concentration of hormone the final events of metamorphosis proceed at their normal pace.

The regulating agent for metamorphosis was thus shown to be the activity of the thyroid gland. But plainly this was not the ultimate control. What regulated the changing rate of activity of the thyroid? Earlier research had already suggested an answer. This regulation must lie in the pituitary gland, which holds the key to stimulation of the thyroid.

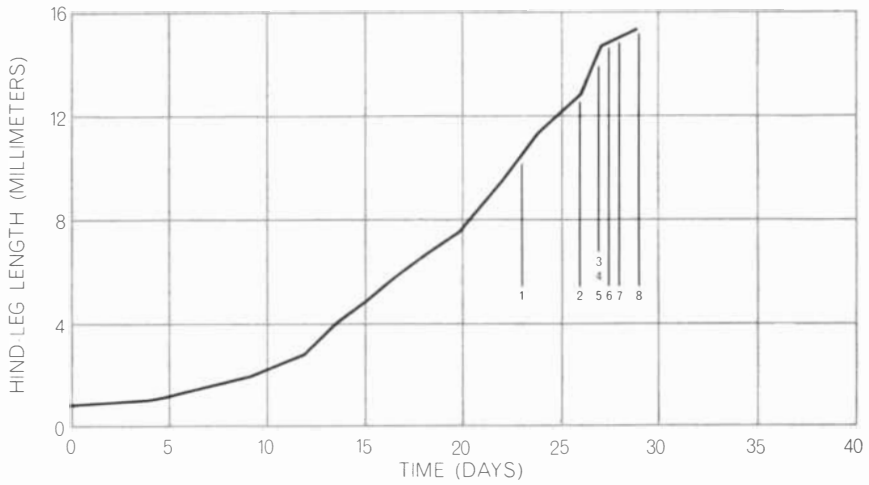
Bennet M. Allen, then working at the University of Kansas, and Philip E. Smith, then at the University of California at Berkeley, had found that tadpoles whose pituitary glands had been removed failed to metamorphose into frogs. (Smith's experiments on tadpoles were the beginning of his classic investigations of the pituitary, which helped to establish the modern science of endocrinology by showing that the pituitary is the master gland regulating many other endocrine organs.) By the time I began my work on metamorphosis it was known that the thyroid's activity is controlled by a pituitary hormone called thyrotropin or thyroid-stimulating hormone (TSH).

What, in turn, regulates the output of TSH by the pituitary? It began to appear that tracking down the control of metamorphosis to its ultimate source might be an arduous task.

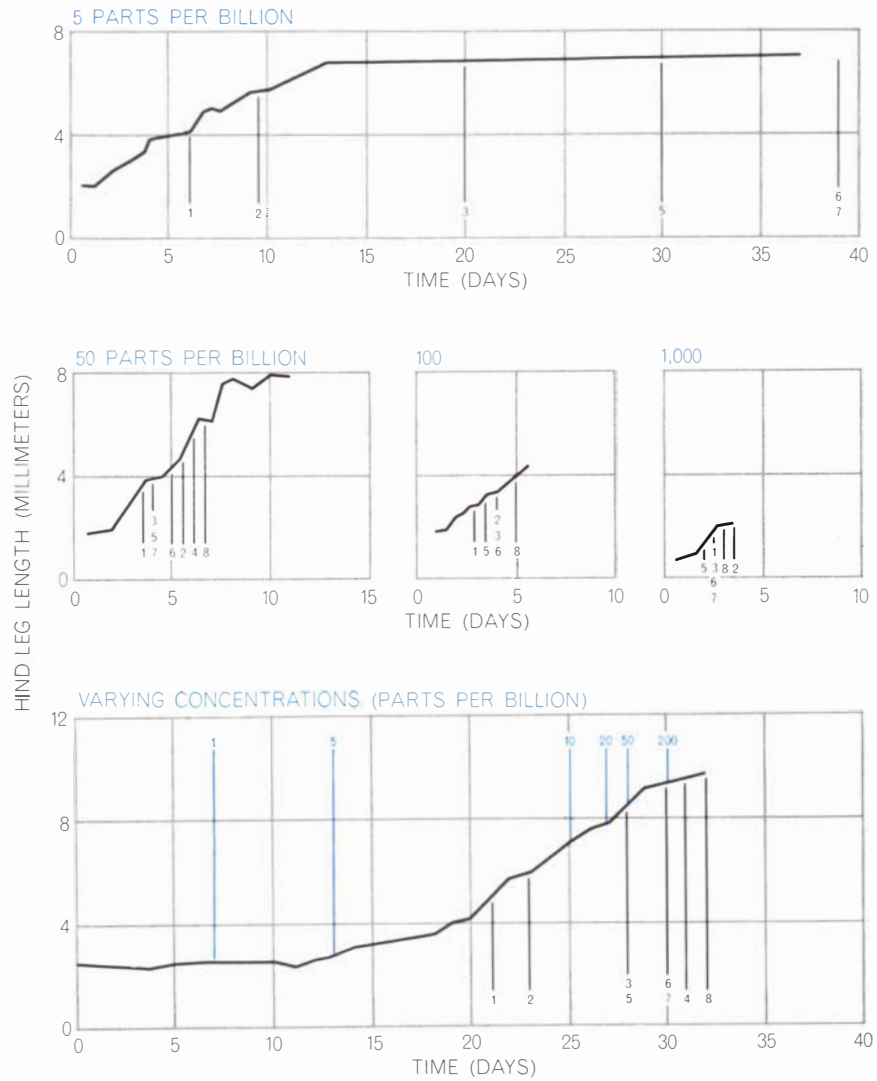
I considered three possible agencies that might stimulate the pituitary's secretion of TSH. The stimulus might come from another endocrine gland, from the brain (to which the pituitary is attached) or from some mechanism



**GRASS FROG (*Rana pipiens*) changes from an aquatic larval form into a terrestrial animal during metamorphosis. The tadpole is shown soon after hatching (*left*) and when it is full-grown, just before metamorphosis (*second from left*). Some 20 days later, late in prometamorphosis, the hind legs are largely developed (*third from left*). The completely transformed frog is shown at the right.**




**SEQUENCE OF EVENTS** in the normal metamorphosis of the Western wood frog (*Rana cantabrigensis*) is plotted with hind-leg length. The events are the reduction (*1*) and complete resorption (*2*) of the anal canal piece, the appearance of a "skin window" for a foreleg (*3*), the emergence of a foreleg (*4*), marked reduction of lips and loss of horny teeth (*5*), loss of horny beaks (*6*) and the beginning (*7*) and completion (*8*) of tail-fin resorption.




**HORMONE CONCENTRATION** governs the rate and sequence of changes in induced metamorphosis. At five parts per billion parts of water (*top*) the changes occur slowly. At high concentrations (*middle*) the changes occur out of sequence and before the legs grow. A normal pattern is approximated (*bottom*) when the hormone concentration is varied.

within the pituitary itself that began to operate when it reached a certain stage of development. To test these hypotheses I removed the tadpole's pituitary from its attachment to the brain and transplanted it to various other sites in the body, performing the operation during the gland's early development in the embryo. The results of the transplantation experiments were tantalizingly ambiguous. Most of the tadpoles eventually showed some leg growth, but their progress toward metamorphosis was long delayed and far slower than normal. Some of the animals simply went on growing as tadpoles without showing any sign of metamorphosis.

The failure of metamorphosis to develop normally indicated that the pituitary's function of promoting metamorphosis was not regulated by hormones from another gland, because such hormones should reach the pituitary by way of the bloodstream regardless of where the pituitary might be located in the body. On the other hand, the fact that many of the tadpoles showed signs of the beginning of metamorphosis, even though the pituitary was transplanted from its normal site on the underside of the brain, suggested that the metamorphic process did not depend on messages from the brain. (Actually, for reasons that will become clear, this interpretation was not valid.)

It seemed, then, that metamorphosis must be controlled by a developmental clock within the pituitary that timed the pattern of the gland's activity. The abnormally slow development of metamorphic changes when the pituitary was transplanted might therefore be due to some transplantation setback that slowed the clock.

Our studies of metamorphosis were interrupted (like a great deal of other work in biology) by World War II. By the time we resumed the investigation in the 1950's various new discoveries in endocrinology and studies of the functioning of the nervous system cast a totally new light on the questions we had been asking. A number of items of information were suddenly found to fit together, like the pieces of a jigsaw puzzle, to form a more meaningful picture of the mechanism of control of metamorphosis.

Tomomasa Uyematsu of the University of Kyoto had performed an experiment somewhat similar to ours. Instead of transplanting the pituitary from its attachment to the brain, he removed the part of the hypothalamus in the brain to which the pituitary is attached. He found that after this op-

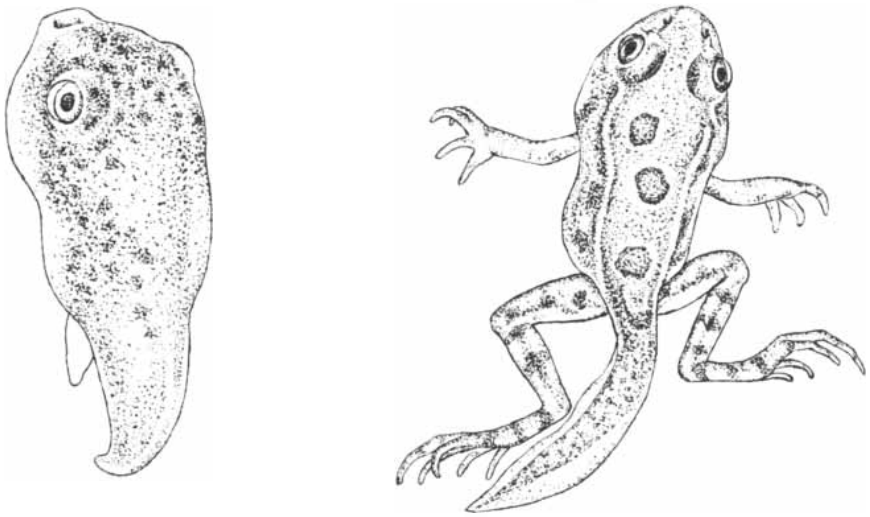
eration the metamorphosis of a toad tadpole could proceed through the early stages, but that the process stopped abruptly when it arrived at the climax stage. We repeated his experiments on frog tadpoles and also explored again the effects of transplantation of the pituitary; in both cases we found that the process of metamorphosis did indeed come to a halt at the beginning of climax.

Uyematsu had supposed that the metamorphic failure was due to degeneration of the pituitary, caused by its disconnection from the brain. In our experiments, however, we found that the pituitary was not impaired and was functional with respect to other hormones it produces. We therefore concluded that the failure of metamorphosis to proceed through climax was simply due to the lack of connection between the pituitary and the brain. This idea was confirmed in experiments on the common spotted salamander: when a barrier was interposed between the brain and the pituitary, the larva of that animal did not metamorphose.

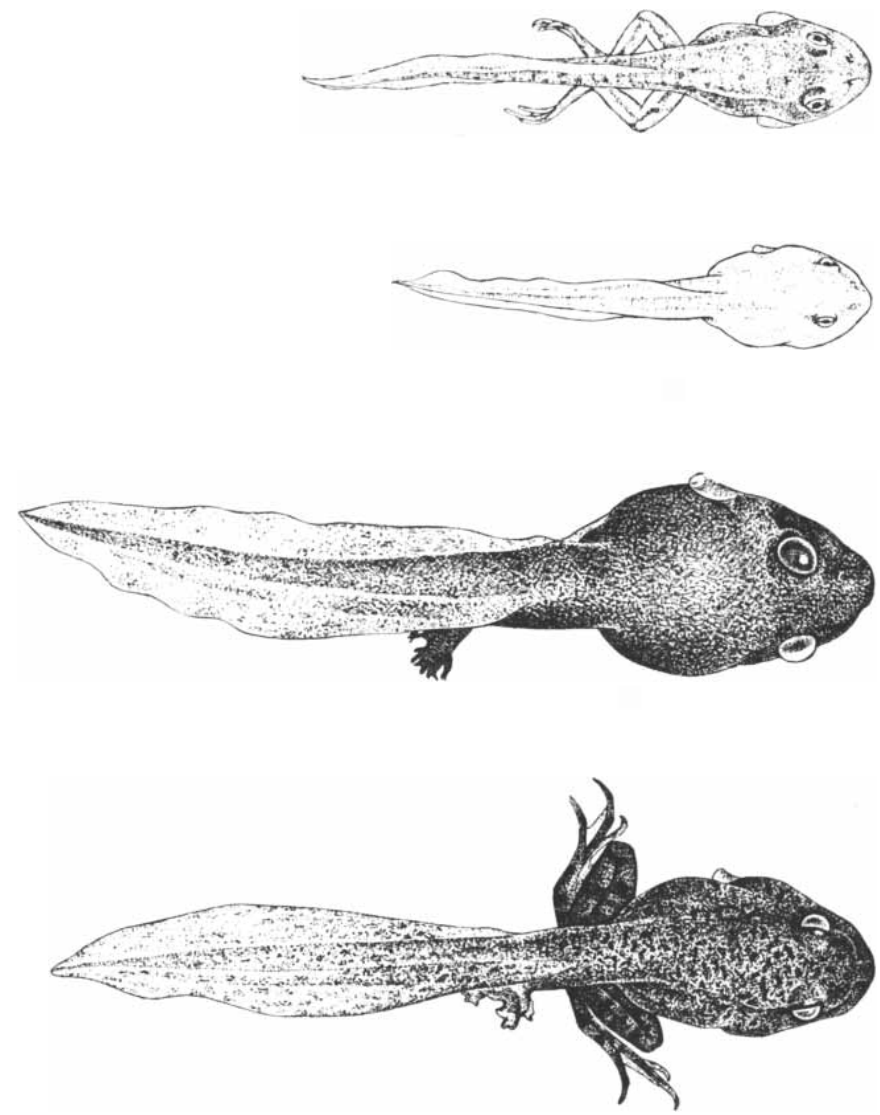
It was now apparent that the brain does, after all, play a controlling role in metamorphosis. From the results of our earlier experiments we had judged that the brain was not involved, because disconnection of the pituitary from the brain did not prevent the development of prometamorphic changes. In retrospect we could see that we had sacrificed those animals (for morphological examination) too soon; if we had kept them for a longer period, we would have observed that the animals could not complete the climax phase of their transformation. Evidently prometamorphosis, requiring only a low level of stimulation by thyroid hormone, could proceed without direct stimulation from the brain, but to induce the metamorphic climax the brain had to stimulate the pituitary to increase its secretion of TSH to a high level and thus step up the thyroid's activity.

How did the brain transmit the stimulus to the pituitary? The answer to this question was surprising indeed. It emerged from two entirely separate discoveries that had intrigued and mystified anatomists for many years.

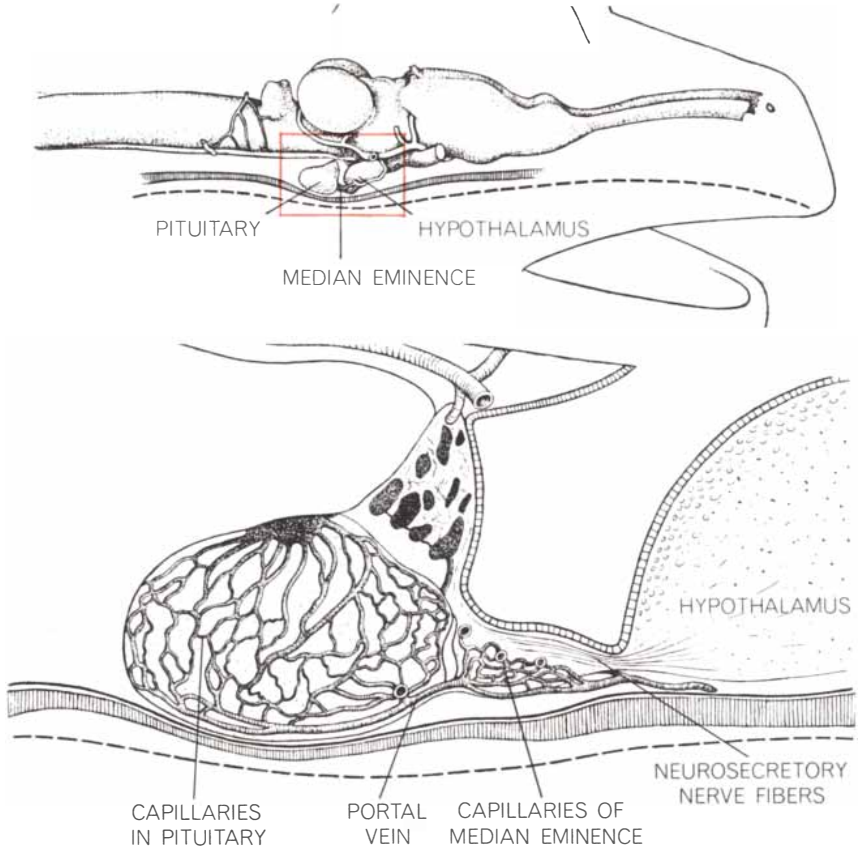
The first of these discoveries, developed by Ernst A. Scharrer and his wife Berta, was that certain nerve cells manufacture hormone-like substances ("neurosecretions") that travel along the nerve-cell fibers and are released at their terminals. The concept that nerve



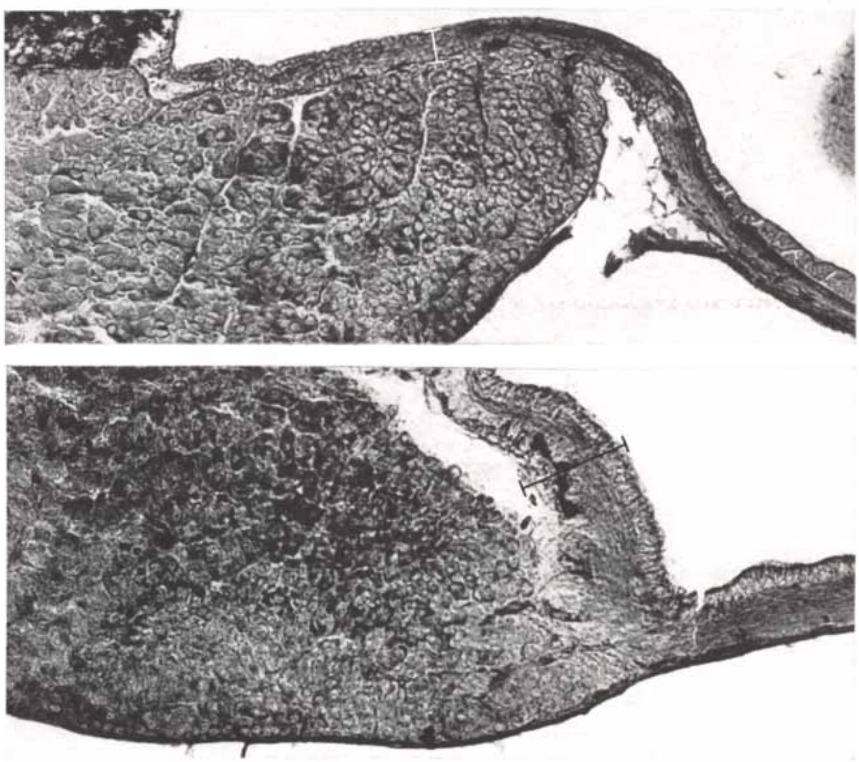
**HIGH CONCENTRATION** of thyroxine causes the tail to be resorbed before the legs have grown and the mouth parts to change in uncoordinated fashion (*left*). Varying the thyroxine concentration from a low to a high level produces more normal metamorphosis (*right*).



**EFFECT OF PITUITARY** on metamorphosis was studied by removing the gland and by transplanting it. A normally metamorphosing tadpole is shown at the top. An animal without a pituitary fails to metamorphose (*second from top*). If the pituitary is transplanted to the tail (*third and fourth from top*), metamorphosis is delayed and varies in different animals.




**PITUITARY GLAND is just under the brain of the frog, behind the hypothalamus (*top*). As shown in the bottom drawing, blood from the capillary net in the median eminence flows out of the hypothalamus through "portal" veins directly into the anterior pituitary.**



**DEVELOPMENT OF MEDIAN EMINENCE is traced in photomicrographs, made by the author, of sections of the bullfrog tadpole pituitary region. Before metamorphosis (*top*) the nervous tissue connecting the hypothalamus and the pituitary (*left*) is thin and undeveloped (*bracket*). By climax (*bottom*) it has thickened and developed into a median eminence.**

fibers might convey messages not only by electrical impulses but also by means of hormones seemed at first utterly bizarre, but it was abundantly confirmed by various kinds of evidence found by other investigators.

The other significant discovery was that the hypothalamus is connected to the anterior lobe of the pituitary by a special set of "portal" veins. In the hypothalamus these vessels receive blood from a net of capillaries within a structure known as the median eminence. Nerve fibers carrying neurosecretions were found to terminate in the median eminence. The blood from the median eminence goes through the portal veins directly to the anterior pituitary, not to the heart. Clearly the nerve fibers, the median eminence and the portal veins provided a channel whereby hormones secreted by the neurosecretory cells in the hypothalamus could be transported to the anterior pituitary without being diluted in the total blood volume. In short, the brain could directly send chemical stimuli to the pituitary.

The Scharrers, putting all the evidence together, developed a general concept that has proved to be one of the most fruitful generalizations of modern biology. (Indeed, I should like to dedicate this article to Ernst Scharrer, who at the time of his death last year was professor of anatomy at the Albert Einstein College of Medicine.) The concept pictures the neurosecretory apparatus as a connecting link between the two major control systems of the body: the nervous system and the anterior pituitary, the master gland of the endocrine system. On the nervous side the key centers are the areas of the brain known as the thalamus and the hypothalamus. The thalamus has aptly been called the Rome of the nervous system, because all roads from the sense organs lead to it. As the headquarters of the sense organs the thalamus receives the information coming in from the environment outside the body. The hypothalamus, just below the thalamus, is the highest receiving center for information from the organs within the body itself. Together the thalamus and the hypothalamus coordinate all the information from outside and inside; on the basis of this integration of information the nervous system forms a strategy of response. It then issues a command that is translated from a nerve impulse into a chemical message by the neurosecretory cells, acting as transducers. The command goes to the anterior pituitary, which transmits the chemical message to the appropriate

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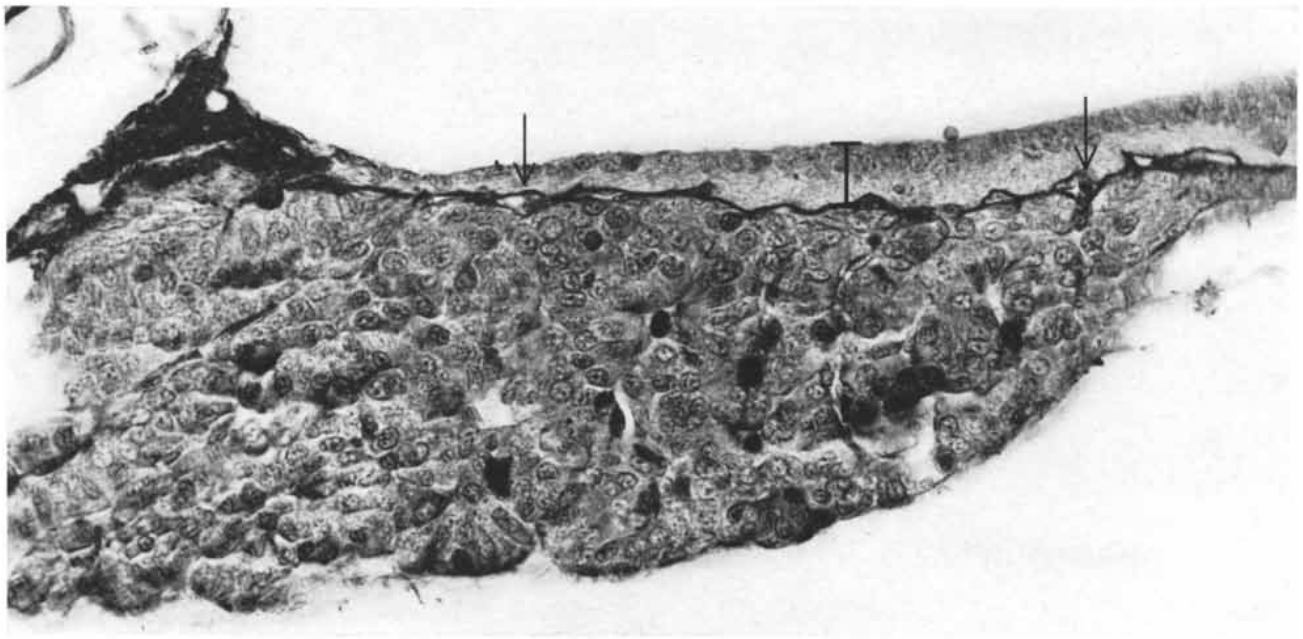
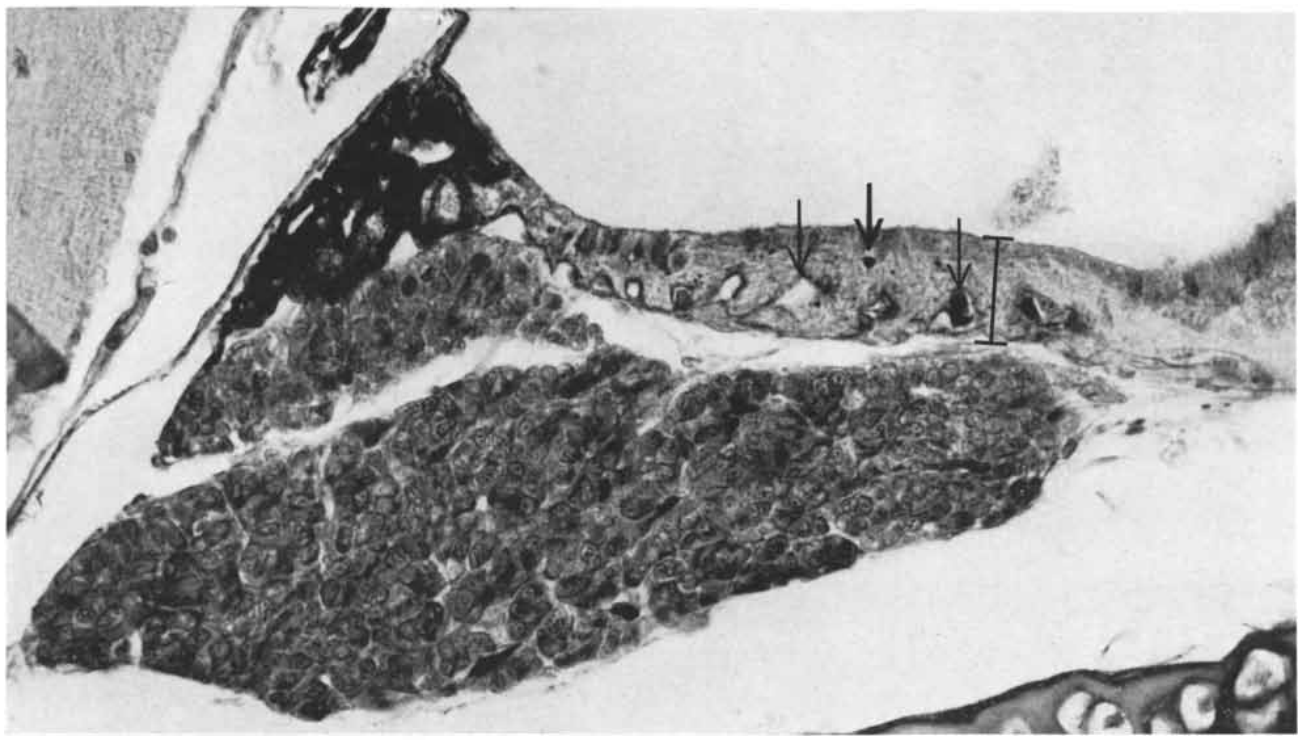
destinations by way of the endocrine system.

All of this puts the question of the mechanism controlling metamorphosis in a new light. It suggests the view that the brain regulates metamorphosis not through nerves but by means of chemical messages passing by way of the portal veins to the pituitary. Much experimental evidence supports this concept. For example, in our experiments with the salamander larva, which showed that the interposition of a barrier between the brain and the pituitary could block metamorphosis, we found that metamorphosis was able to proceed normally when the animal regenerated blood vessels that bypassed the barrier. Many laboratories have established that in mammals the hypo-



**REMOVAL OF THYROID** not only prevents metamorphosis but also prevents the development of the median eminence. This photomicrograph made by the author shows the pituitary region in a thyroidectomized grass frog tadpole. A thin layer of nervous tissue (*bracket*) extends over the anterior pituitary from the hypothalamus, with a thin network of capillaries (*arrows*) between them.



**THYROXINE TREATMENT** of a thyroidectomized tadpole caused metamorphosis and also, as demonstrated by this photomicrograph, development of a median eminence. The thin layer of nervous tissue has thickened (*bracket*) and is drained by a network of capillaries (*light arrows*) that can carry neurosecretory material (*heavy arrow*) to the portal veins for delivery to the pituitary gland.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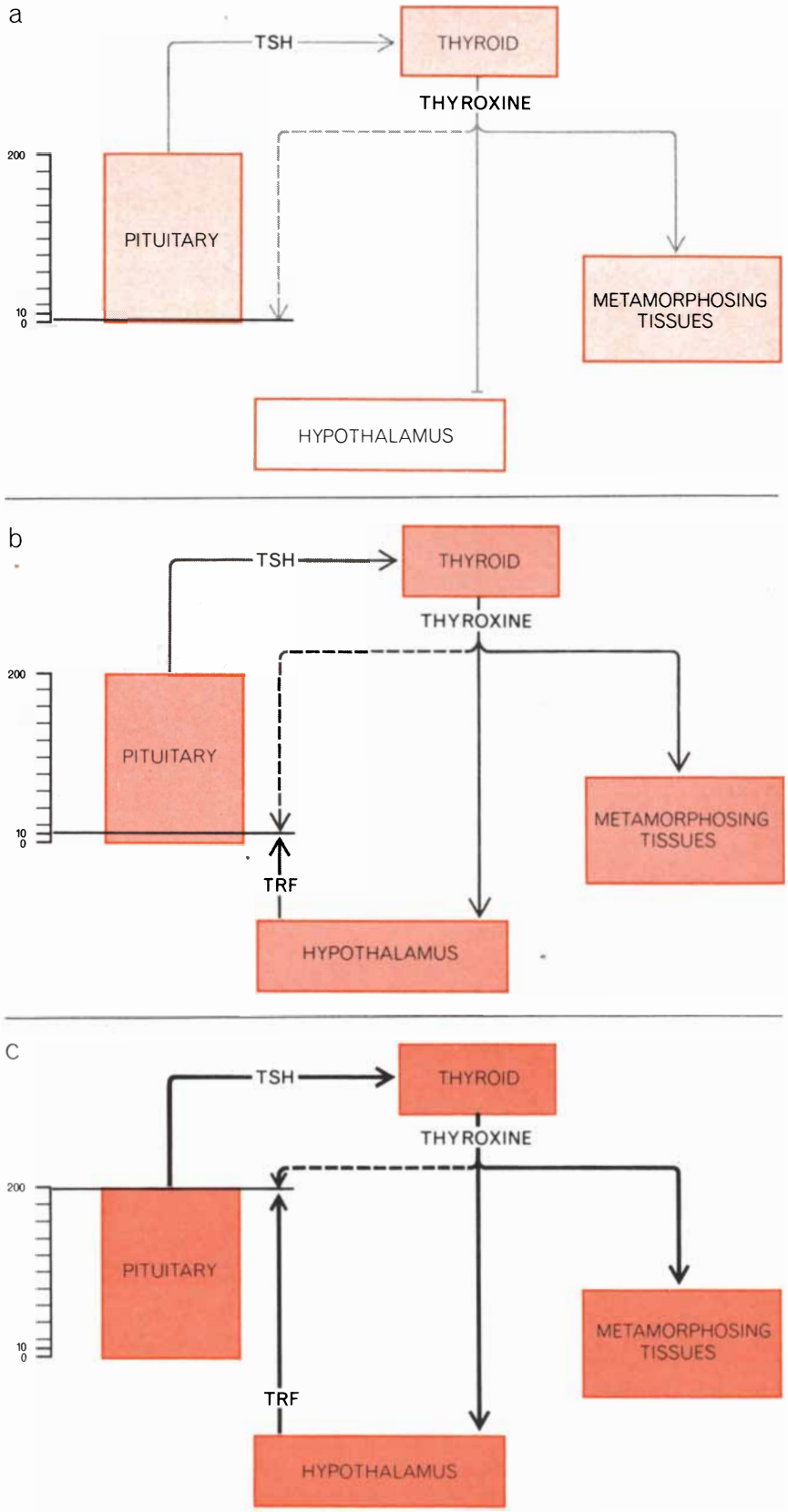


**FEEDBACK MECHANISM** that regulates metamorphosis is pictured at three stages. Before metamorphosis (*a*) the hypothalamus is insensitive to thyroxine stimulation. Pituitary TSH activity is inhibited by thyroxine; the "thyrostat" (*left*) is low. In prometamorphosis (*b*) the sensitized hypothalamus produces TRF under thyroxine stimulation; the TRF counteracts thyroxine inhibition of the pituitary and the thyrostat rises. The positive feedback loop builds up to an explosive production of thyroxine during the climax phase (*c*).

thalamus produces a chemical messenger, thyrotropin-releasing factor (TRF), that regulates production of TSH by the pituitary.

We have not yet, however, reached the end of the story. It seems that we have definitely traced command of the metamorphosis of the tadpole into a frog back to the hypothalamus. The transformation is directed by the thyroid, which in turn is controlled by the pituitary, which in turn is controlled by the hypothalamus. But what gives the order to the hypothalamus? Do we still have to search back further through some seemingly endless chain of command?

Examination of the anatomy of the tadpole gave a new direction to our thoughts on this question. We noted that young tadpoles lack a fully developed median eminence between the brain and the pituitary such as is found in the adult frog. This part of the neurosecretory apparatus does not develop until the prometamorphic stage that launches the tadpole's transformation. Since the median eminence seems an essential part of the transformation apparatus, we naturally asked: What stimulates the development of the median eminence?

We found that removal of a tadpole's thyroid, which was already known to prevent metamorphosis, also prevented development of the median eminence. On the other hand, when we administered thyroxine to a full-grown tadpole that had been thyroidectomized, the median eminence did develop. These results indicated that a positive feedback mechanism operates in the tadpole: the thyroid hormone causes the median eminence to develop and that structure in turn stimulates the pituitary to activate the thyroid to produce more hormone.

A positive feedback system of this kind will lead to an intense buildup of activity. This is precisely what we observe during the process of metamorphosis. From a level of activity that is extremely low before metamorphosis, the thyroid builds up through intermediate levels during prometamorphosis to an explosive release of hormone at climax.

Was the thyroid hormone really the stimulus that primed the cycle of metamorphic activity? As an experiment to test this hypothesis we tried administering thyroxine to young tadpoles to see if this would initiate a precocious development of the mechanism that caused them to metamorphose. The stratagem

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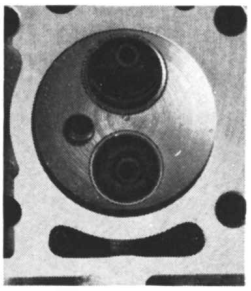

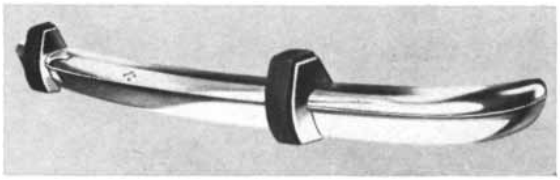

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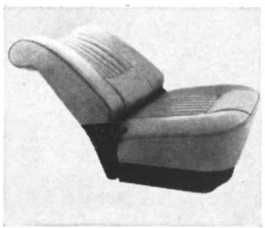

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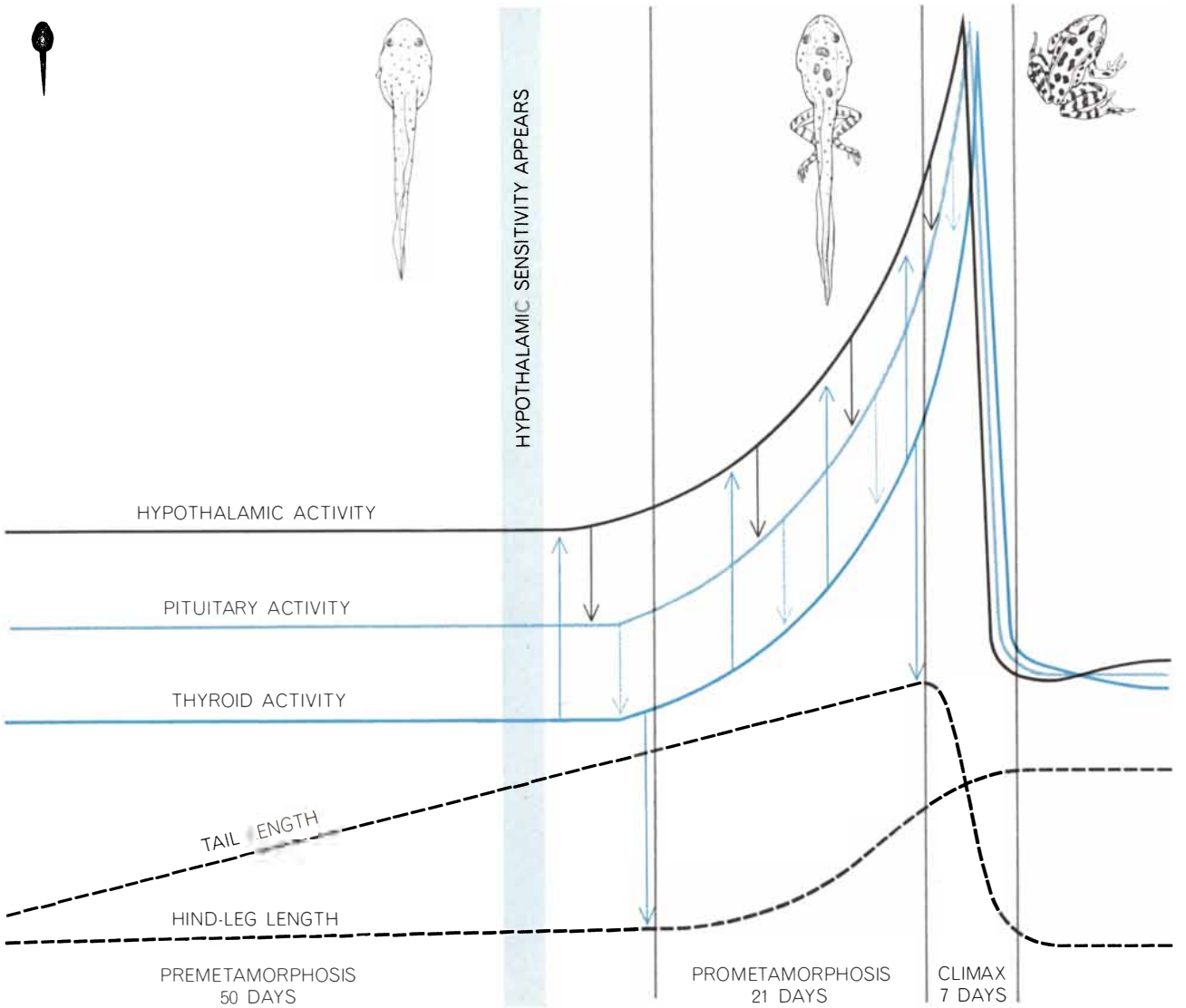


**INTERACTIONS of the hypothalamus, pituitary and thyroid and the effect of thyroid hormone on metamorphosing tissues are illustrated schematically. Hormone cycling begins when the hypothalamus becomes sensitive to thyroxine. Soon enough thyroxine is being secreted to cause hind-leg growth and then resorption of the tail. The buildup of thyroid activity continues until the metamorphic system, like the other tissues, has completely matured, when its sensitivity to thyroxine ceases and hormone levels drop rapidly.**

failed to induce such development. The failure led to the suggestion that perhaps the hormone could trigger the mechanism only after the tadpole had reached a certain stage of maturity. We therefore tested the effect of the hormone on development of the median eminence in tadpoles of various sizes and ages, and in this way we found that the animals showed a change in sensitivity to the hormone during growth. The median eminence of the tadpole of the grass frog, for instance, did not respond to thyroxine when the animal was smaller than 40 millimeters in length; it responded slightly at a size of 45 millimeters; at a size of 50 millimeters (five millimeters, or one week in time, before it would normally enter prometamorphosis) the tadpole responded to the extra dose of thyroxine with full development of the median eminence.

We have arrived, then, at a reasonably clear outline of the metamorphic mechanism. At a critical point in the tadpole's development some factor, presumably controlled by a genetic mechanism, renders the hypothalamus sensitive to the low level of thyroid hormone circulating in the animal's body. The neurosecretory apparatus of the hypothalamus responds by releasing a TRF substance that stimulates the anterior pituitary to secrete TSH, which turns on the orderly increase of thyroid secretion. That increase trips the orderly sequence of tissue changes that transforms the tadpole into a frog.

In actuality the feedback relations between hypothalamus, pituitary and thyroid may be still more complex. There is much evidence to indicate that thyroid hormone acts directly on the pituitary to inhibit its production of TSH. This negative feedback system keeps the level of thyroid hormone and TSH in balance with each other at a level that is determined by the sensitivity of the pituitary to thyroid inhibition. In analogy to the operation of a thermostat this system has been called a "thyrostat." It is evident that the TRF substance of the hypothalamus could be the agent that regulates the thyrostat level, and thus the rate of metamorphosis, by changing the sensitivity of the pituitary [*see illustration on page 84*].

Of course there are many questions still to be answered. How is the sensi-

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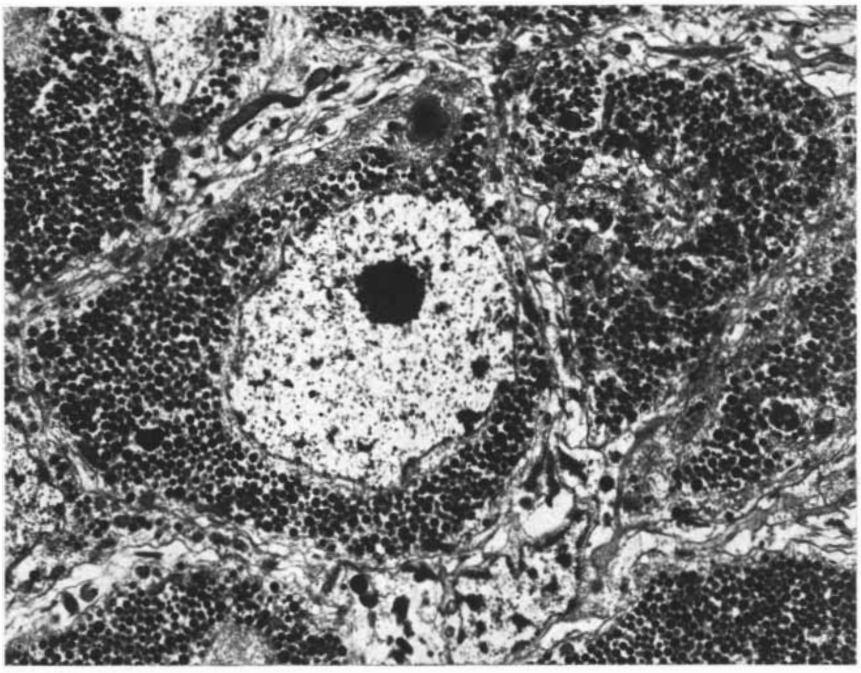
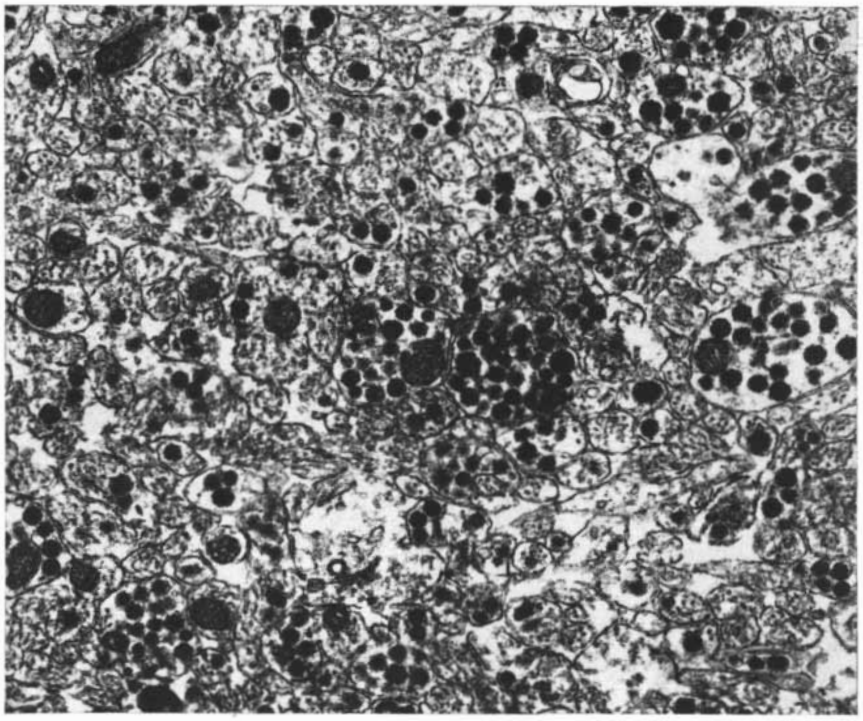
tivity of the hypothalamus to the thyroid hormone turned on? Just how does the hormone bring about the metamorphic changes in tissues? What accounts for the diverse ways in which different tissues respond to the stimulus? What, for example, explains the fact that the hormone causes the tadpole's jaws to grow rapidly while at the same time it causes the lips, gills and tail to be resorbed? The investigation of metamorphosis brings us face to face with some of the most fundamental questions in biology.



**NEUROSECRETORY CELLS in the brain of an earthworm are enlarged 7,000 diameters in this electron micrograph made by the late Ernst A. Scharrer and Stanley Brown of the Albert Einstein College of Medicine. Neurosecretory granules fill the cytoplasm of each cell.**



**GRANULES can be seen inside the axons, or nerve fibers, of the hypothalamus of a toad tadpole in this electron micrograph made by Jack Rosenbluth. The axons, enlarged 22,500 diameters, are seen in cross section. The dense, dark gray structures are mitochondria.**

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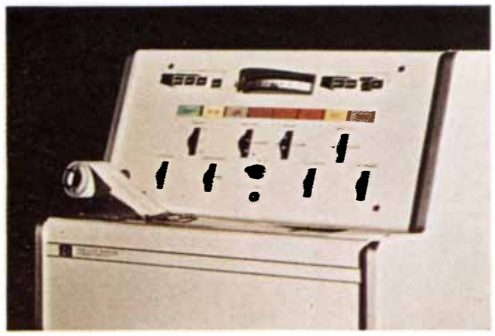

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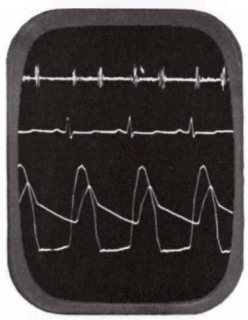

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EXCAVATORS' HANDICAP at Mohenjo-daro is the presence of groundwater near the surface of the plain. This cut was made to uncover the bottom of the city wall (brickwork at rear). The work was halted by flooding at a depth of only 15 feet below the plain level.

# THE DECLINE OF THE HARAPPANS

## While Egypt and Sumer prospered, a state of greater size was swept away in South Asia. Aryan invaders have traditionally received the blame; it now appears that instead the Harappans were flooded out

by George F. Dales

Four thousand years ago the world's first three civilizations were flourishing. The Sumerians of Mesopotamia and the Egyptians of the Nile valley are reasonably well known to us. The third civilization embraced an area more extensive than either Egypt or Mesopotamia, yet it is far less known. Its most impressive remains—the dead cities of Mohenjo-daro and Harappa in the Indus valley of what is now West Pakistan—were first excavated four decades ago [see "A Forgotten Empire of Antiquity," by Stuart Piggott; SCIENTIFIC AMERICAN, November, 1953]. Our knowledge of this remarkable culture of South Asia, which is called the Harappan civilization, has been limited until recently to what could be gleaned from archaeological findings at these two sites, mainly because the written records of the culture are scanty and not yet deciphered. New discoveries in both Pakistan and India, however, are now adding much to our understanding of certain events in Harappan times.

In the past few years many Harappan towns and villages have been discovered well outside the civilization's nucleus in the Indus basin, indicating that the Harappan state extended much farther than earlier investigators had realized. It is now known that Harappan authority reached westward at least to the modern border between Iran and Pakistan, that it touched the foothills of the Himalayas to the north, even extending to the headwaters of the Ganges, and that it stretched southward along the west coast of India as far as the Gulf of Cambay to the north of modern Bombay. The Harappan civilization thus controlled or dominated a triangle roughly 1,000 miles on a side [*see illustration on next page*]. A series of carbon-14 dates from Harappan sites along the coast of India also shows that many of these southerly towns and trading posts had continued to be occupied much later than the sites in the Indus valley. This and other bits of unexplained evidence have raised doubts concerning a fundamental hypothesis about the Harappan civilization: that Harappa and Mohenjo-daro had been sacked, and the Harappan civilization liquidated or absorbed, by the Aryan invaders who presumably brought the Indo-European language and culture to prehistoric India sometime during the second millennium B.C.

With the intention of learning more about the life and death of Harappan civilization the University of Pennsylvania and the Pakistan Government Department of Archaeology agreed on a joint reopening of the Mohenjo-daro site during the winter of 1964–1965. The expedition undertook, as part of a three-year program, to determine the total depth of the site's deposits of human occupation, something earlier workers had been unable to establish because groundwater lies only 15 feet below the surface of the plain at Mohenjo-daro. Efforts were made to devise some means of excavating these flooded occupation levels and to analyze evidence at the site, in the form of abundant accumulations of water-deposited silt, that the city had more than once been exposed to major floods.

During its mature period, from a few centuries before to a few centuries after 2000 B.C., the city of Mohenjo-daro housed an estimated 40,000 inhabitants in an area about a mile square. Today its ruins consist of two parts; a western mound that contains the so-called citadel is separated by a broad gully from a much larger eastern mound that contains the lower town [*see illustration on page 95*]. At the southwest corner of the lower-town mound an undisturbed area rises some 35 feet above the surrounding plain. In 1964 this area was selected for excavation in the hope of obtaining a sequence of stratified materials that could be correlated with the artifacts unearthed by earlier expeditions.

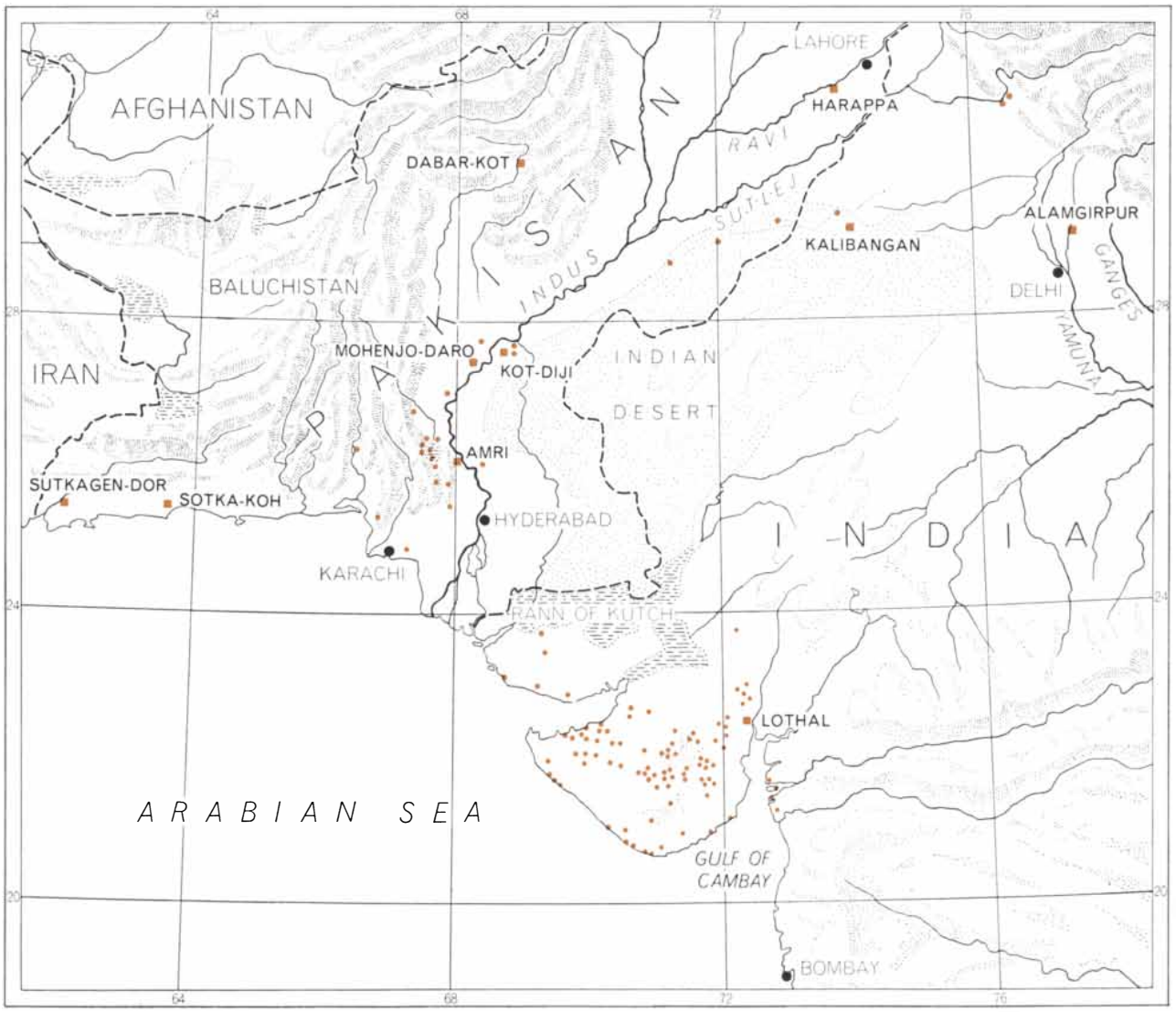
As a start it was decided to sink drill holes straddling the selected area to discover the depth of the earliest occupation levels. Core samples were collected at two-foot intervals; before the drills struck sterile soil 39 feet of core containing evidence of occupation had been raised to the surface. Thus the total depth of occupation in this part of Mohenjo-daro is 74 feet, about the equivalent of a seven-story building. Of the entire deposit, the deepest and therefore the earliest 24 feet (or almost a third) is still not available for study because of groundwater.

In the 1920's and 1930's, when the first digging was done at Mohenjo-daro, carbon-14 dating techniques were unknown and the only firm evidence of the city's antiquity came from the discovery of a few Harappan artifacts, principally stone seals, in ancient Mesopotamian sites. The Harappan seals found in reliably dated Mesopotamian strata belonged to a period extending from about 2350 B.C. to about 1800 B.C. The early investigators concluded that Mohenjo-daro and Harappan civilization in general had flourished during this same period. The carbon-14 dates now available for a number of Harappan and pre-Harappan sites tend to confirm this dating but also suggest that from 50 to 100 years might be added at each end of the period. When several new carbon samples collected from late

levels at Mohenjo-daro in 1964–1965 are analyzed, they should establish the date when that city—and civilization in the southern Indus valley—met its end.

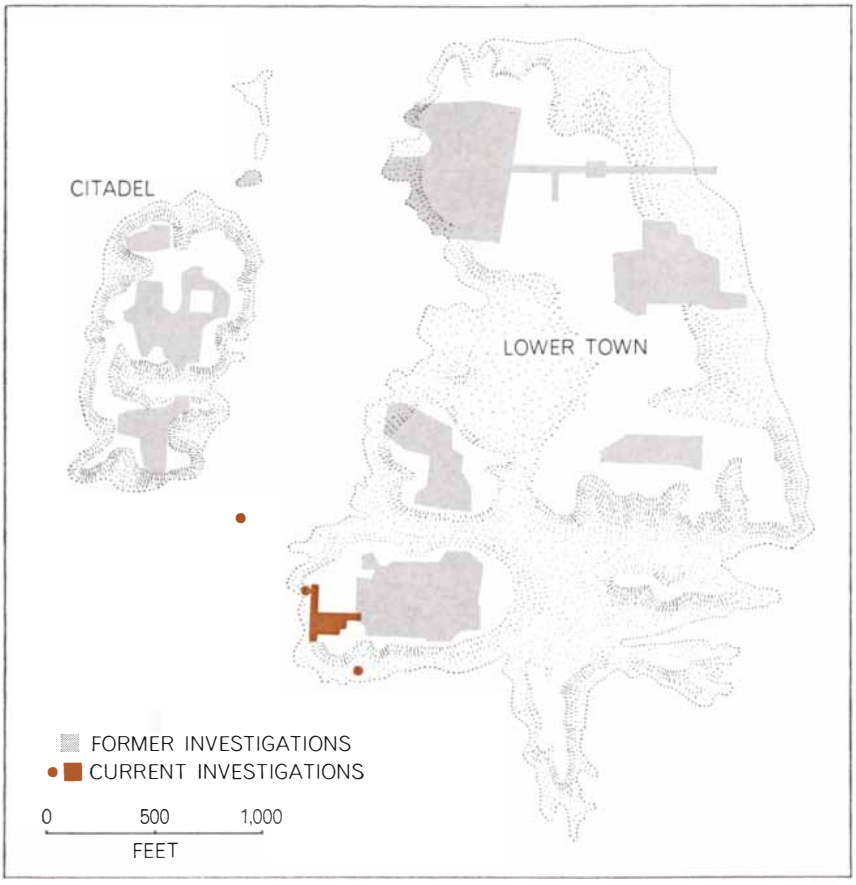
Before discussing why and how Harappan civilization declined, something should be said about its origins. No formative phase, or early stage, of Harappan culture has yet been positively identified in the archaeological record of South Asia, although current excavations in Pakistan and India are beginning to yield some clues. Numerous pre-Harappan cultures have been found in the hills and valleys of Baluchistan, to the west of the Indus valley. Pre-Harappan groups also lived in the Indus valley itself just before Harappan culture appeared there in mature form. The Baluchistan sites have strong ties with Afghanistan and the Near East, but their relation to the origin and development of Harappan civilization is little understood. The same is true of the civilization's precursors in the Indus basin. At sites such as Amri, Kot-diji and Kalibangan materials belonging to the mature Harappan phase are found mixed with materials from late phases of the indigenous cultures. Such findings suggest that Harappan civilization arrived full-blown from some other area. At the same time earlier levels of these and other pre-Harappan Indus sites contain objects that are characteristic of Harappan civilization in its maturity. These findings argue either for an on-the-spot evolution from one culture to the other or, at the very least, for heavy borrowing from the local inhabitants by the Harappans when they first settled in the Indus valley. Perhaps the 24 feet of waterlogged occupation layers at Mohenjo-daro, containing as they should a record of the city's earliest development, will help to illuminate this question of Harappan origins.

The problem of the decline and disappearance of Harappan civilization has been a matter of primary concern during the expedition's first two years of work. One of the discoveries made at Mohenjo-daro in the 1920's that is cited in support of the hypothesis that Aryan invaders destroyed the Harappan civilization was the presence of some 30 human skeletons in what appeared to be the upper levels of the site. The bodies had evidently been left where they fell rather than receiving burial; this seemed a dramatic archaeological confirmation of the postulated invasion and massacre. In 1964 the poorly preserved remains of five more bodies were unearthed in




**HARAPPAN CIVILIZATION at its maturity some 4,000 years ago controlled a triangular territory with sides roughly 1,000 miles long. The Indus valley was its central focus; Harappa, near modern Lahore, and Mohenjo-daro to the south were its great cities.**

the upper levels of the excavation, only two to three feet below the surface of the mound. They lay in a narrow alley amid an accumulation of collapsed brick, broken pottery and ash. The period to which these dead belong is evidently late, but it has not yet been precisely determined. The fact that they had not had any normal kind of burial suggests that all five were the victims of some common disaster. Nonetheless, we are reluctant to believe that either the earlier discoveries or our own support the hypothesis of an Aryan invasion. For one thing, no one has any exact knowledge of the date when the Aryans first entered the Indus valley area; they have not yet been identified archaeologically. For another, the sole purpose served by the invasion hypothesis is to explain the demise of Harappan civilization. If evidence can be found that Mohenjo-daro declined for other reasons, the invasion hypothesis goes by the board. Such evidence, in the form of traces of catastrophic floods, is now being subjected to close scrutiny.



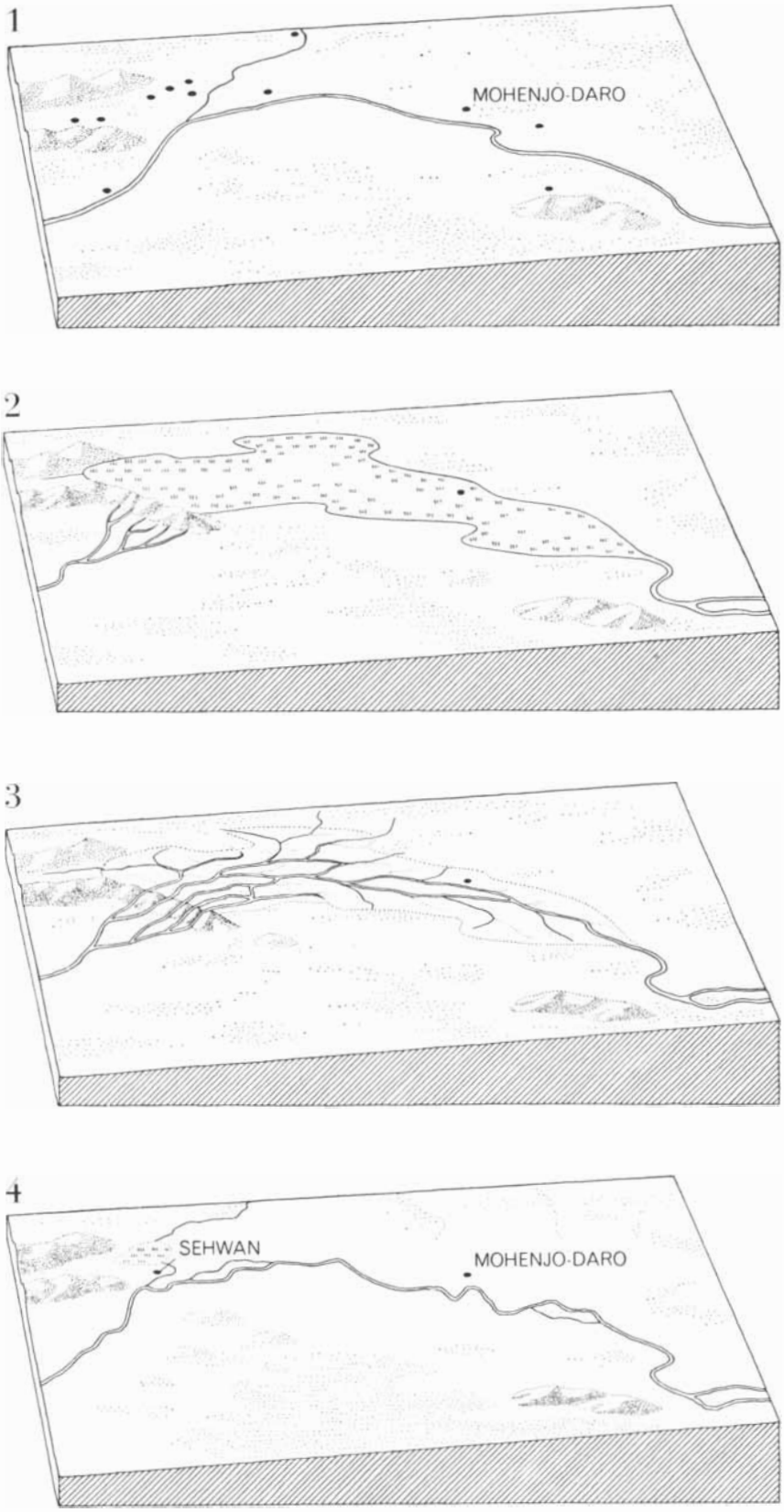

**URBAN AREA of Mohenjo-daro is divided into the citadel district to the west and a larger district, called the lower town, to the east. The part of the lower town that was excavated in 1964 and the location of three test borings are shown in color. In this part of the site the culture-bearing strata are 72 feet thick; 24 feet of the accumulation is under water.**

The presence of water-deposited silts at Mohenjo-daro had been recognized by early workers at the site as an indication that floods had played a role in the city's history, but no one suggested that the silts represented anything more significant than periodic brief overflows of the Indus River. Excavators who later worked at such sites to the south of Mohenjo-daro as Amri and Chanhu-daro found abundant evidence of flooding in these areas also. It was not until 1940, however, that anyone suggested a relation between the archaeological evidence of ancient floods and a number of topographic and geological anomalies of the Indus valley. In that year the Indian paleontologist M. R. Sahni noticed silt deposits perched many feet above the level of the Indus plain near the city of Hyderabad in what is now West Pakistan. This and other evidence suggested to him that the area's ancient floods had not been mere river overflows but events on a far larger scale. Major tectonic upheavals, Sahni proposed, might have blocked the Indus River from time to time; each such stoppage would have caused the gradual formation of a huge upstream lake that might then have persisted for decades.

Sahni's suggestion went virtually unnoticed until 1960. By that time two totally independent lines of research had led to the identical conclusion: natural disasters must have played a major role in the decline of Harappan civilization. In that year the University Museum undertook an archaeological survey of the Arabian Sea coast of West Pakistan. The field party discovered settlements of the Harappan era that had clearly been seaports but were now located as far as 30 miles inland. These displaced ports made it evident that the coastline in this part of Pakistan had risen considerably during the past 4,000 years, with the initial rise apparently having occurred during the Harappan period. In the same year Robert L. Raikes, a hydrologist, was conducting extensive surveys in southern Baluchistan and the lower Indus valley. Raikes's keen antiquarian interests led him to investigate the possibility that ancient topographic changes in the area might well be related to the decline of Harappan civilization. The mutual desire to combine archaeological evidence with the findings of another discipline led to a joining of forces. Raikes is now working with the Mohenjo-daro expedition as engineering consultant and is in charge of geological and hydrological investigations.

Just as Sahni had been puzzled by the silts near Hyderabad, so Raikes in 1964 sought an explanation for the thick silt deposits that are preserved in the ruins of Mohenjo-daro at points as high as 30 feet above ground level. The 1964 test borings that revealed the thickness of the underlying archaeological strata at the site showed that silt deposits also existed below the surface of the plain. When the layers above ground are added to those below, the silts sandwiched between the city's successive occupation levels span a vertical distance of 70 feet. A better explanation than occasional floods is obviously needed to account for such a multilevel accumulation.

Raikes's preliminary research not only suggests that the dam-and-lake hypothesis proposed 25 years ago by Sahni is tenable but also singles out an area near Sehwan, some 90 miles downstream from Mohenjo-daro, as the most probable area of tectonic disturbance




**PERIODIC FLOODING of Mohenjo-daro and other Harappan settlements in the Indus River valley was apparently caused by geologic disturbances in the vicinity of modern Sehwan. In *1* the Indus follows an unhindered course to the sea (*south is at left, north at right*). In *2* a massive mud extrusion or a rock fault dams the river and produces a shallow, marshy lake upstream, flooding Mohenjo-daro. In *3* the lake waters have topped the barrier; as it erodes, the lake empties. In *4* the cycle is complete and the valley is habitable again.**

affecting the city. Both at Mohenjo-daro and at smaller sites between the city and Sehwan the silt deposits are of the kind characteristic of still-water conditions in a lake rather than the kind deposited by the fast-moving waters of a flooded river. Moreover, there is abundant geological evidence of rock faulting on a large scale near Sehwan. The faulting by itself could have raised a natural dam and turned the upstream portion of the Indus into a slow-filling lake. More probably, however, the same disturbances that caused the faulting were accompanied by massive extrusions of mud, aided by the pressure of accumulated underground gases. Such mud extrusions are not uncommon in Pakistan even today; for example, a number of mud islands abruptly appeared off the Arabian Sea coast in 1945.

Let us assume that some such barrier was thrown up near Sehwan. Thereafter the normal discharge of the Indus would not have reached the sea but instead would have accumulated in a steadily growing reservoir [*see illustration at left*]. As the rising waters encroached on the valley's villages and towns, many small settlements undoubtedly disappeared below the surface and were completely obliterated by silt. When the waters approached such a major population center as Mohenjo-daro, however, it seems logical to suppose that efforts were made to protect the city. The archaeological evidence strongly suggests that large-scale community projects were indeed undertaken at Mohenjo-daro for this purpose. As an example, massive mud-brick platforms were erected and faced with fired brick, apparently with the objective of raising the level of the city safely above the lake waters. One such embankment, partially excavated by the expedition in 1964, is some 70 feet wide and well over 25 feet high [*see top illustration on opposite page*].

Eventually the waters accumulating behind the natural dam would have risen until they had spilled over it and begun to cut it away. Thereafter the Indus would have resumed its normal flow to the sea and re-erosion of the silt-covered floodplain would have begun. After each immersion the inhabitants of Mohenjo-daro found it necessary to rebuild or reinforce most of the city's buildings. Although they usually rebuilt directly on top of the older foundations and walls, they eventually encountered serious problems of decay and sinking. The ruins today dramatical-

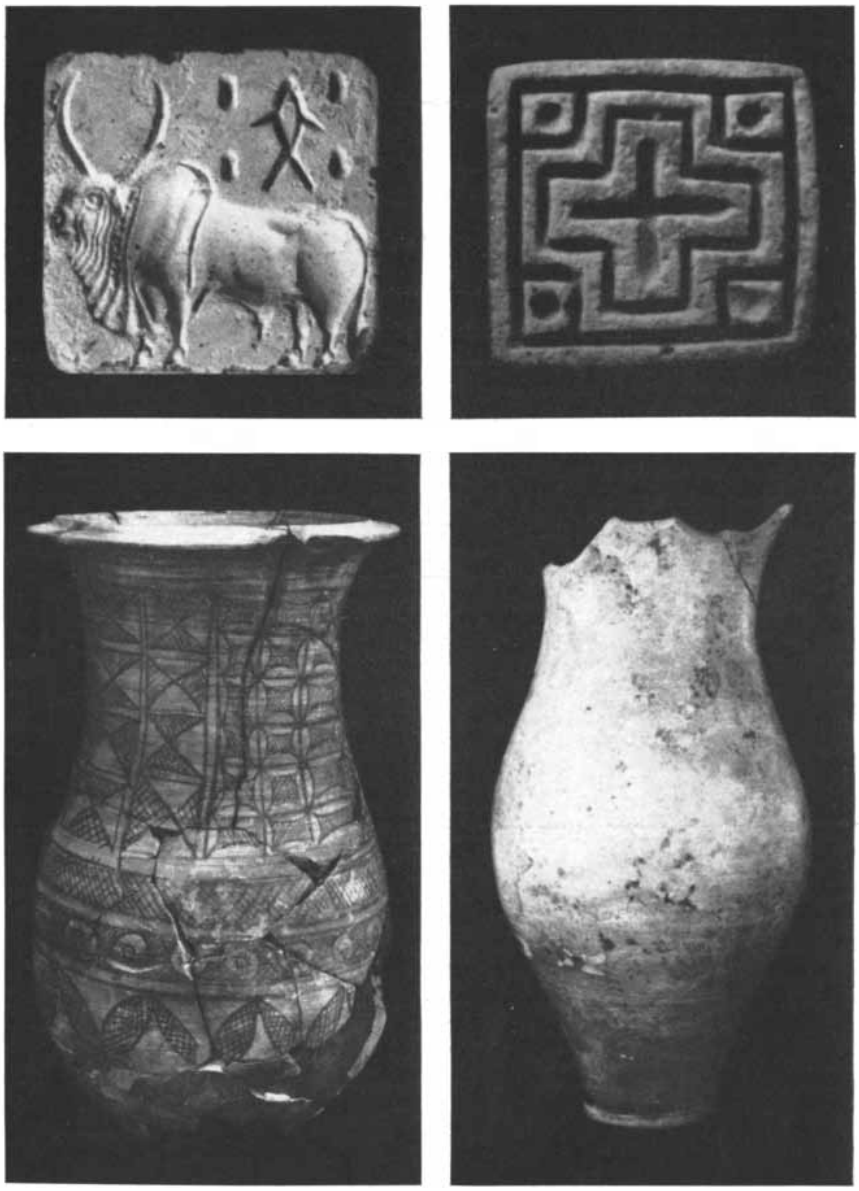
FLOOD COUNTERMEASURES taken at Mohenjo-daro included the construction of massive brick embankments to keep the level of the city above water. A pit (*center*) was dug down through 25 feet of unfired brick in one such embankment without reaching bottom.

FLOOD DAMAGE at Mohenjo-daro is evidenced by slumping brick masonry (*center*), which presumably reflects erosion of the city's unfired brick foundations during their prolonged immersion in lake water. The Harappans simply leveled masonry and built on top of it.

ly illustrate the problems they faced [*see bottom illustration on preceding page*].

Both the multiple layers of silt at Mohenjo-daro and the evidence of multilevel reconstruction suggest that the city was flooded in this prolonged and damaging fashion no less than five times and perhaps more. At present it is impossible to estimate just how long each cycle of lake intrusion and withdrawal may have lasted, but it seems doubtful that the duration of any one cycle would have exceeded 100 years.

Could such a series of natural catastrophes, rather than the Aryan invasion, have brought about the collapse of Harappan civilization? The city of Harappa itself and lesser sites in the Indus valley to the north of Mohenjo-daro do not seem to have ever suffered significant flooding. Instead they give the appearance of having been abruptly abandoned, after which they stood empty for centuries. Such a pattern is certainly compatible with the invasion hypothesis. It is also compatible with a situation in which the Harappan state's weakened heartland to the south was unable to send help to the inhabitants of the northern frontier when they were threatened. The people who presented the threat could quite well have been hill raiders rather than Aryan invaders. An archaeological fact must also be taken into account in any effort to reconstruct the Harappan demise: The northern Indus sites show no evidence of a decline in material prosperity before their abandonment but quite the opposite is true of Mohenjo-daro and other southern sites. What does this contrast signify?



**HARAPPAN DECLINE is reflected in the lowered standards of workmanship characteristic of the late Harappan phase. A skillfully carved stone stamp seal of the mature Harappan phase (*top left*) is contrasted with a simple geometric one (*top right*), typical of the late phase at Mohenjo-daro. A similar contrast is seen between a polychrome painted pot of the mature phase (*bottom left*) and an unpainted pot from late-phase levels (*bottom right*).**

The mature phase of Harappan civilization at Mohenjo-daro appears to have degenerated into a well-defined late phase that in turn fades into a squatter phase. Both the materials and style of later artifacts and the quality of later architecture demonstrate a gradual process of degeneration. The traditional Harappan painted pottery of the mature phase, with its intricate black-on-red designs, is replaced in the late phase by plain unpainted ware. In contrast to the typical seals of the mature phase, carved out of soapstone and superbly engraved with animal figures in negative relief, the late-phase seals are not made of soapstone and bear only a few simple geometric designs. The deftly executed and spirited animal figurines of the mature phase are replaced by much cruder effigies. Even the buildings erected during the squatter phase reflect the same degeneration: they are jerry-built and often made of broken or secondhand bricks. These examples of diminishing prosperity in the south, or at least of a debasement in the Harappan civilization's standard of values, suggest an associated breakdown in the efficiency of state administration. Perhaps not only Harappan prosperity but also the Harappan spirit was being mired in an unrelenting sequence of invading water and engulfing silt.

What was the final fate of the Harappans? Findings at more than 80 Harappan sites recently identified in the Gujarat area of India provide a partial answer. A majority of the Indian sites belong to the late phase of Harappan civilization, but the culture had also been present in force in this area during its mature phase. The seaport at Lothal, for example, contains the largest structure of fired brick erected anywhere in the Harappan realm; it is identified by its excavator as a docking basin, ingeniously designed so that the ships within it remained afloat even at low tide.

With the onset of the late phase of Harappan civilization the Gujarat sites present a sad picture of gradual

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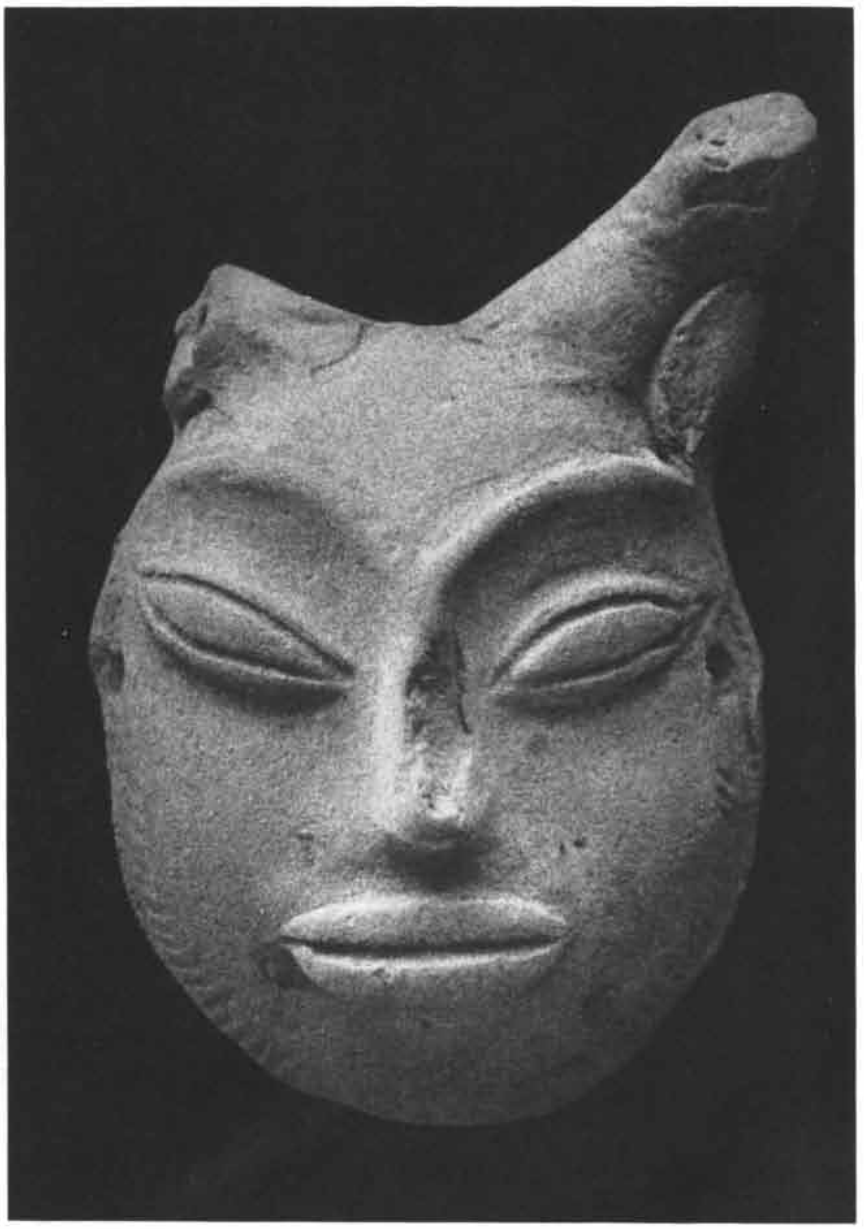

**HARAPPAN ARTISTRY is exemplified by this miniature terra-cotta mask, one and a half inches wide, found at Mohenjo-daro in 1964. Typical of mature Harappan workmanship, the mask has a boldly outlined human face topped by the ears and horns of some animal.**

degeneration. Sophisticated Harappan traits are watered down by a mingling with impoverished local cultures until what was once distinctively Harappan is diluted to the point of nonexistence. No urban centers rise along the Gulf of Cambay, no more soapstone seals are carved, no more clay figurines are modeled. Trade with the civilized centers of the Near East, once the *raison d'être* for these Indian coastal ports, comes to a stop. The Harappan script, with its 400 or so still undeciphered symbols, disappears.

These findings are compatible with a hypothesis that envisions the disastrous sequence of floods at Mohenjo-daro and elsewhere in the southern Indus valley as the stimulus that drove the Harappans from the heartland of the far-flung state to take refuge in the Gujarat area. Suddenly crowded with refugees and deprived of support from the once prosperous realm that had fostered them, the Harappan trading towns on the southern frontier could have done little else than gradually merge with the countryside they had formerly dominated. On the basis of present evidence it seems probable that the Harappans, to borrow a figure of speech from T. S. Eliot, met their end not with an Aryan bang but with an Indus expatriate's whimper.

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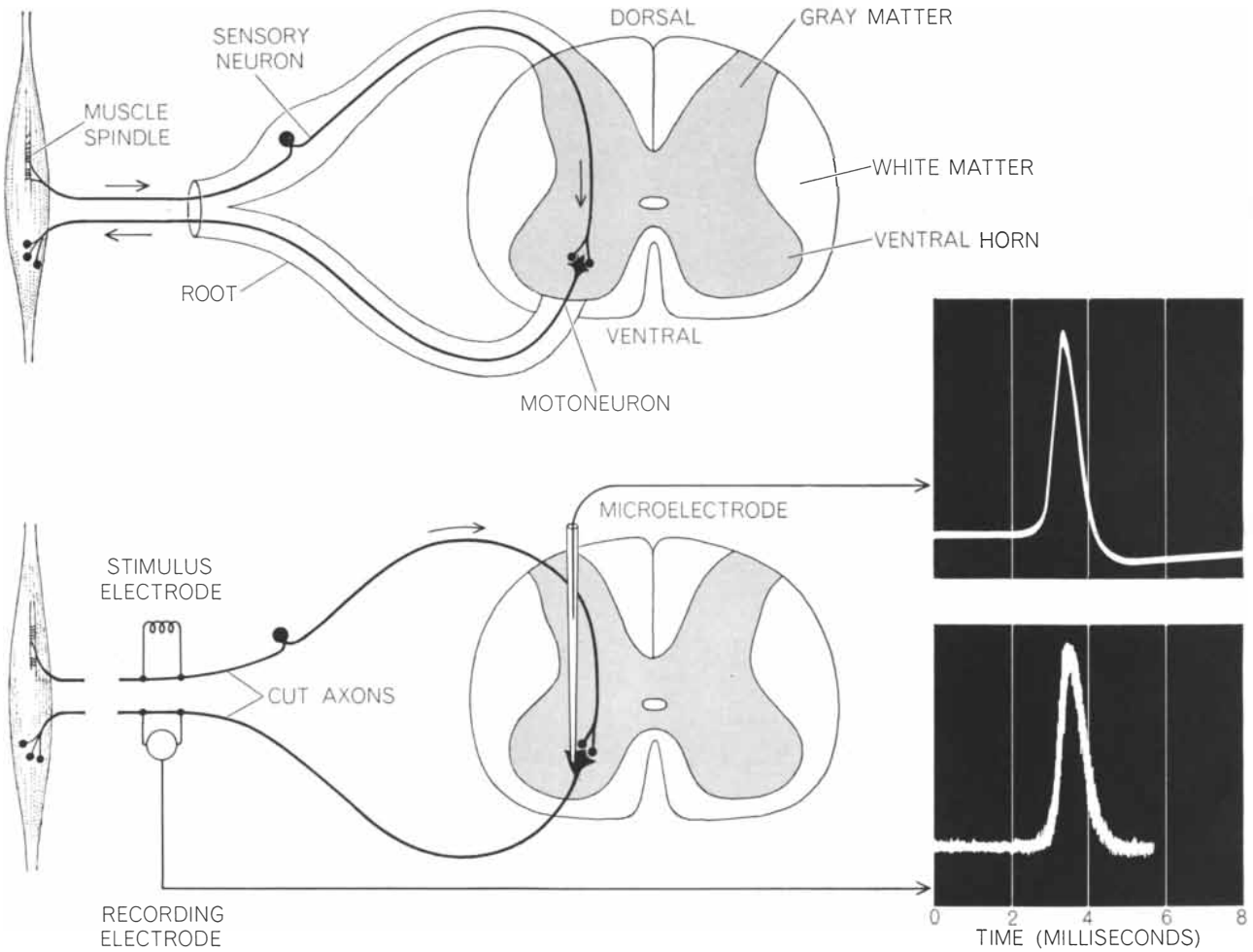
# Inhibition in the Central Nervous System

*In muscular action some muscles must be stimulated to contract and others must be inhibited from doing so. In vertebrates this inhibition occurs at the level of the brain and the spinal cord*

by Victor J. Wilson

Muscular responses, from the simplest reflex movement to the most refined and complex voluntary behavior, depend on the excitation of nerve cells in the brain or the spinal cord. A stimulus is detected by appropriate receptors; activation of the receptors leads to the discharge of nerve impulses along "afferent" axons (the nerve fibers leading to the central nervous system), where the impulses cause the excitation of motoneurons (the large nerve cells whose "efferent" axons innervate the voluntary muscles of the body); excitation of motoneurons leads to muscular contraction, and so the response to the stimulus occurs. Excitation and contraction alone, however, cannot accomplish even the simplest reflex response; something more is needed. If a response involves two muscles



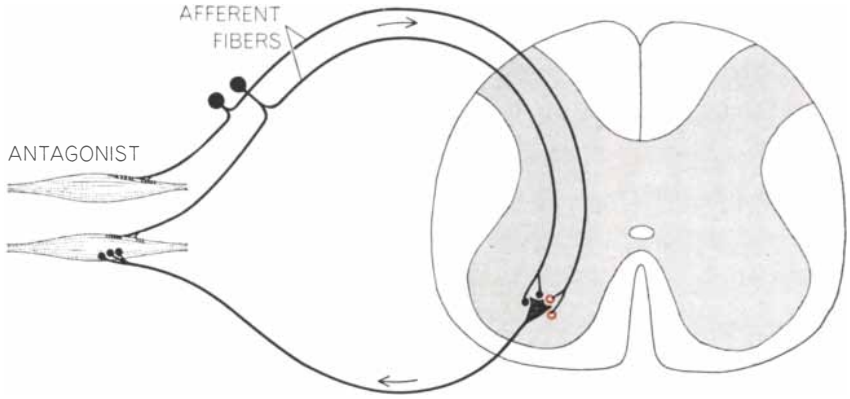

**MONOSYNAPTIC PATHWAY of the stretch reflex consists of two neurons: a sensory cell and a motoneuron (*top*). Impulses from the muscle spindle, which is sensitive to stretching, excite the motoneuron, impulses from which cause contraction of the muscle. The reflex is elicited experimentally by electrical stimulation of cut fibers (*bottom*). The response can be measured with a microelectrode inside a single motoneuron or with electrodes on the cut motoneuron fibers. Typical records of both kinds are shown at right.**

acting at a joint, for example, one as a flexor and the other as an extensor, it usually happens that one muscle contracts while its antagonist relaxes. Relaxation of the antagonist is the result of an important process that is indispensable in the regulation of many aspects of animal activity: nervous inhibition.

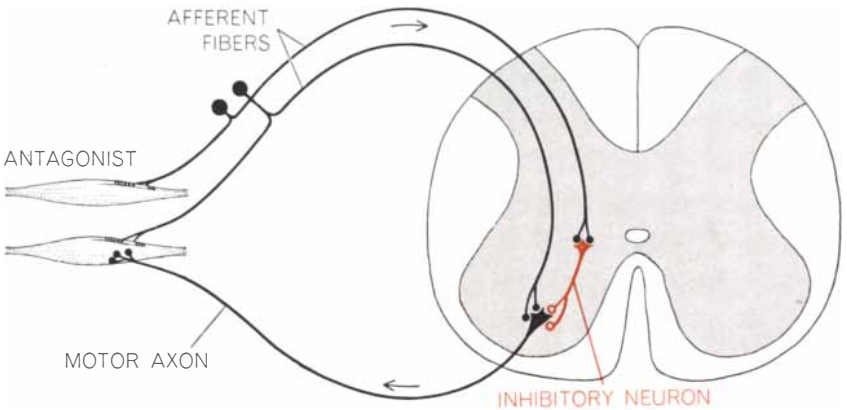
The inhibition of muscular contraction occurs at different sites in various animals. In crustaceans, for example, there are peripheral inhibitory nerves, the excitation of which decreases the activity of muscles they affect. In vertebrates too there are some nerves that inhibit muscles, but they are all in the involuntary nervous system that controls the activity of the heart muscle and of the "smooth" muscles of the digestive tract, vascular system and other internal organs. If any efferent nerve of the voluntary nervous system that controls the "striated" skeletal muscles is excited, the muscle it supplies will contract. In other words, there are no peripheral inhibitory nerves; inhibition affecting the voluntary muscles must reside within the central nervous system. Central inhibition was first analyzed by Sir Charles Sherrington, on whose work present-day reflex physiology is based. This article will consider ways in which such inhibition is accomplished.

A vertebrate striated muscle consists of a large number of muscle fibers, many of which are innervated by one motoneuron. The impulse delivered to a muscle fiber by the firing of an excited motoneuron causes the fiber to contract; as was first shown by E. D. Adrian and Detlev W. Bronk at the University of Cambridge in 1929, the extent and the strength of a muscle contraction depend on the number of motoneurons involved and the frequency with which they discharge impulses. The inhibition of a response stems either from a reduction of the excitability of the motoneurons themselves or from a reduction of the excitatory input reaching them.

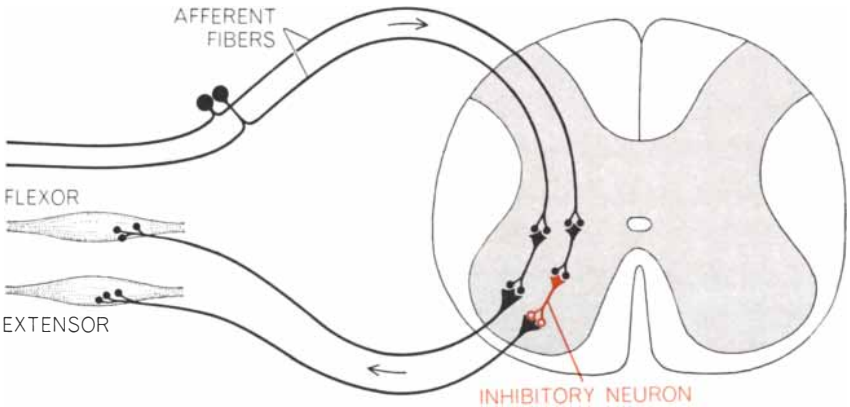
Inhibition of the first type takes place at the synapse, or the junction between two nerve cells. Impulses in the "presynaptic" fiber—the terminal of an axon leading to the motoneuron—release a chemical transmitter that affects the membrane of the "postsynaptic" element—the motoneuron or one of its branches called dendrites—in such a way that the excitability of the motoneuron is reduced. This is called postsynaptic inhibition. In the second type of central-nervous-system inhibition the impulse in the presynaptic fiber is interfered with and reduced before it reaches the synapse; this is called presynaptic inhibition. Most of the work in our laboratory at Rockefeller University has involved postsynaptic inhibition, and that is what I shall discuss first.




**INHIBITORY COMPONENT of the stretch reflex was once assumed to be monosynaptic, with nerve fibers from an antagonist muscle forming inhibitory synapses with motoneurons.**



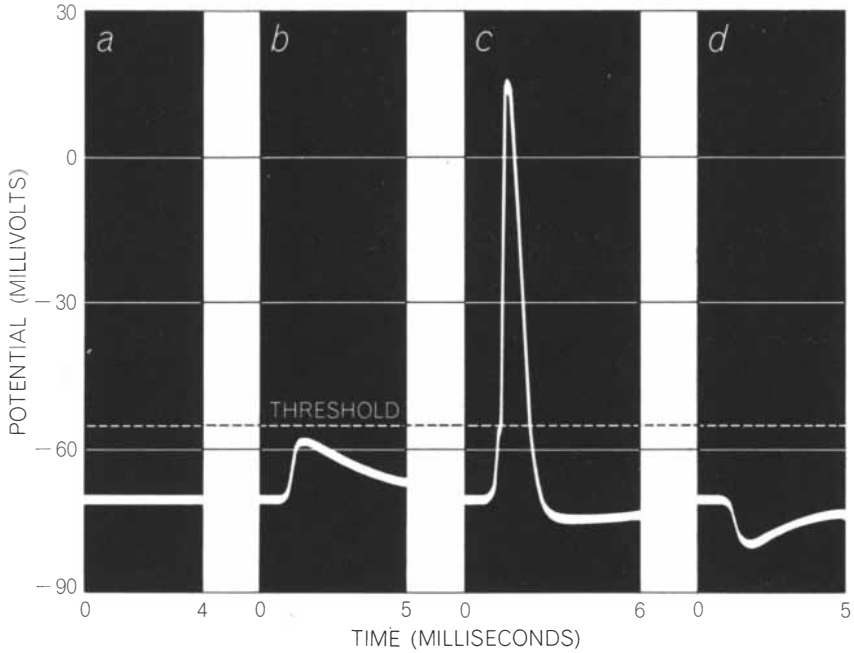

**INHIBITORY INTERNEURON is now generally believed to be involved in inhibition in the stretch reflex. Such a neuron (*color*), excited by an afferent fiber, inhibits a motoneuron.**




**WITHDRAWAL REFLEX, such as the flexing action that follows painful stimulation of an extremity, involves a more complex inhibitory pathway. At least one excitatory cell intervenes between a sensory fiber and a cell (*color*) inhibiting an extensor motoneuron.**

The most satisfactory test system in which to study postsynaptic inhibition is known as the monosynaptic stretch reflex. The simplest reflex pathway in the spinal cord, as Birdsey Renshaw showed at the Rockefeller Institute in 1940, is a monosynaptic, or two-neuron, arc consisting of a fiber from a sensory neuron forming a synapse with a motoneuron [*see illustration on opposite page*]. In 1943 David P. C. Lloyd, also at the Rockefeller Institute, demonstrated that the two-neuron arc was the element involved in the stretch reflex, the active contraction that occurs in any muscle subjected to stretching.

The monosynaptic reflex can be



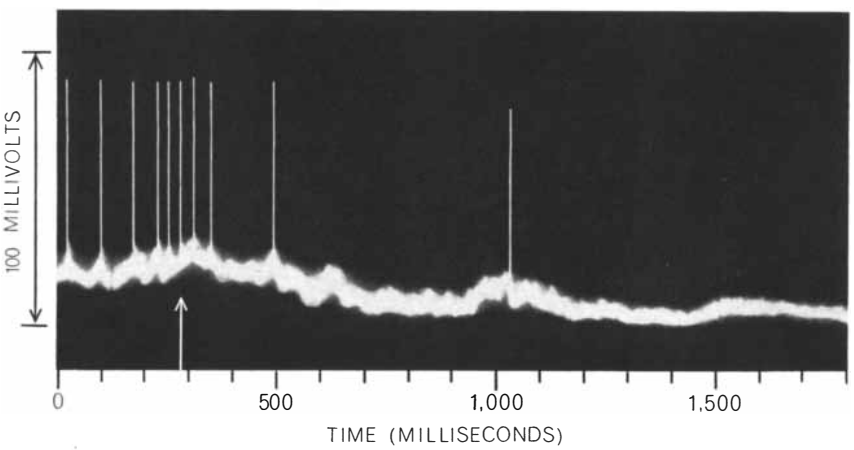

**MICROELECTRODE inside a motoneuron measures the membrane potential. In a motoneuron at resting potential (*a*) stimulation of afferent fibers from a muscle affected by that motoneuron causes an excitatory postsynaptic potential to appear (*b*). If the potential reaches threshold, an action potential, or nerve impulse, is produced (*c*). Stimulation of afferent fibers from an antagonist muscle produces an inhibitory postsynaptic potential (*d*).**

elicited in an animal not only by stretching a muscle but also by more readily measured experimental stimuli. An afferent nerve leading from a muscle is cut and the "central" end (on the side of the cut closer to the spinal cord) is stimulated electrically. The reflex response is measured by recording the electrical activity at the central end of the efferent nerve, the bundle of motoneuron axons, which has been cut where it leaves the spinal cord [*see illustration on page 102*]. A few milliseconds after the stimulus is administered the response appears on an oscilloscope as a synchronized discharge—the sum of the impulses from the group of several hundred motoneurons innervating a given muscle.

As Renshaw first suggested, the size of the monosynaptic reflex can be considered an index of the excitability of the population of cells whose discharge gives rise to it. If one assumes that some fraction of the cells (although not always the same cells) will usually respond to a test shock, a series of such shocks provides a set of fairly stable control responses. If the group of motoneurons is "facilitated" by some change in the input to it, the population will become more excitable, a test shock will discharge more cells and the reflex will be larger than normal. If an inhibitory process decreases the group's excitability, a stimulus will discharge fewer cells and the reflex will be smaller. Lloyd carried out detailed studies of the organization of spinal reflexes with a monosynaptic testing method based on these principles.

The excitation of the stretch receptors called muscle spindles not only evokes a stretch reflex in a muscle but also inhibits the response of its antagonist—the muscle that would otherwise counteract the reflex movement. That is to say, stimulation of the large afferent nerves from one muscle inhibits the monosynaptic reflex of the muscle's antagonist. This occurs even if no part of the simple test system has been activated before the stimulus is applied, so the inhibition cannot be due to the fact—as was once thought possible—that the nerves involved are in the refractory or subnormal states that typically follow a period of excitation. It must be a true inhibition, an effect that Lloyd first demonstrated in 1941.

Reciprocal inhibition of an antagonist as part of the stretch reflex is one instance of a functionally meaningful inhibitory action. There are others. If a muscle is strongly stretched, a new set of receptors—the tendon organs—is activated. Impulses initiated in these receptors lead to inhibition of the response of the very muscle that has been stretched, ending active resistance to the stretching. Such inhibition is more diffuse in its distribution than the antagonist inhibition that follows activation of muscle spindles. Still more diffuse is the inhibition that occurs as part of what is called the withdrawal reflex. If a painful stimulus is applied to an animal's foot, the entire leg is withdrawn from the stimulus by a strong bending action. To achieve this the flexor muscles of the leg contract while the extensors are inhibited. The inhibitory pathway in this situation is composed of more elements than the inhibition associated with the simple stretch reflex, and it is also distributed over many more segments of the spinal cord and to more muscles.

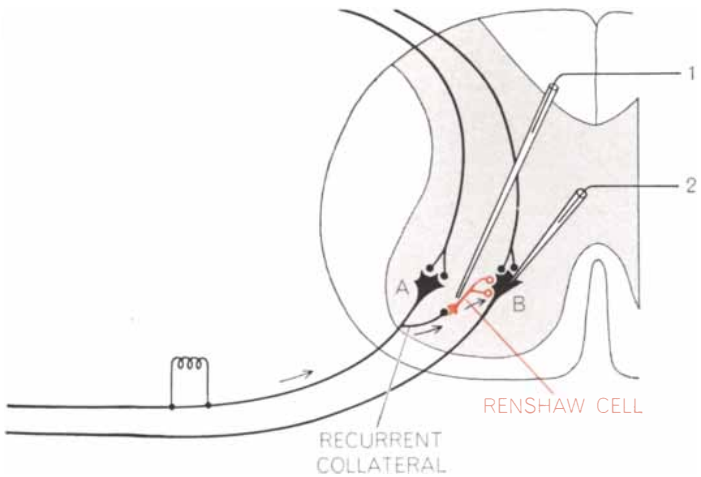


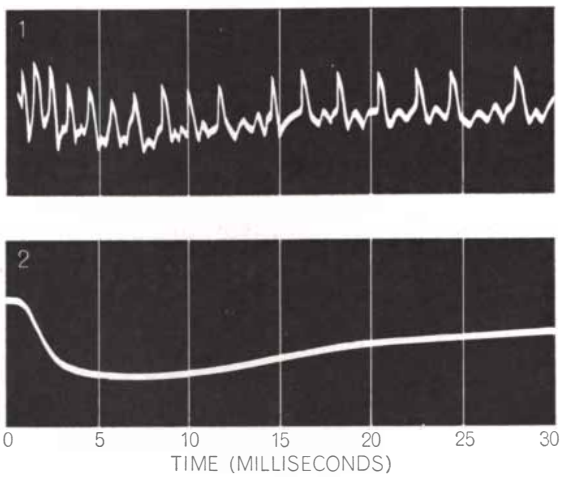

**INHIBITION of a motoneuron in response to a strong pinch is shown in this oscilloscope trace made by W. H. Talbot at Rockefeller University. Before the stimulus (*arrow*) the cell was extremely active, steadily discharging action potentials. The pinch caused polarization, or negative deflection of the membrane potential, stopping the cell's discharges.**

For some years it was generally believed that the inhibitory action associated with the stretch reflex was

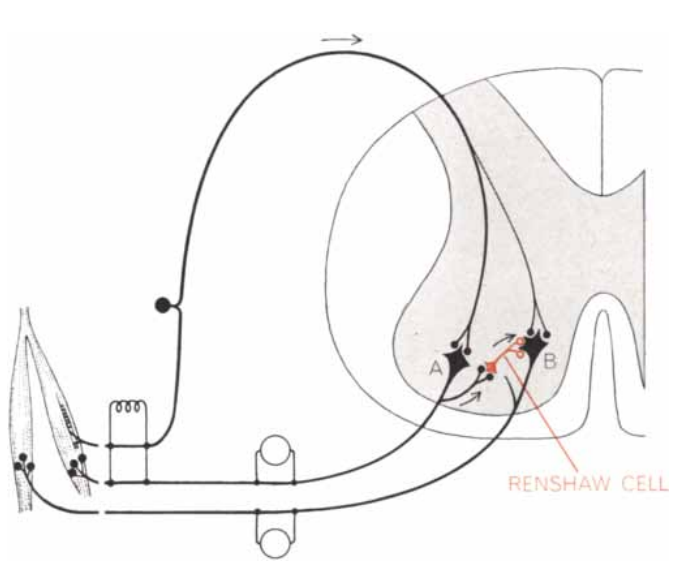
monosynaptic, like the reflex itself [*see top illustration on page 103*]. As a result of more recent experiments it is now widely—although not universally—thought that even this simplest of all inhibitory pathways contains one more cell: a specialized inhibitory "interneuron." (An interneuron is a cell that does not send its axon outside the spinal cord.) The Australian nerve physiologist Sir John Eccles has set down as a postulate that all postsynaptic pathways in the mammalian central nervous system have such an inhibitory neuron as their final link, that an inhibitory neuron acts to inhibit all cells with which any of its terminals synapse, and that just as excitatory cells liberate at their terminals a specific chemical transmitter that modifies the postsynaptic membrane so as to bring about excitation, inhibitory cells liberate a different transmitter that modifies the membrane in a different way to bring about inhibition. These are among the important conclusions of an extensive series of investigations by Eccles and his collaborators that began in the early 1950's and capitalized on a powerful new electrophysiological tool, the ultrafine microelectrode.

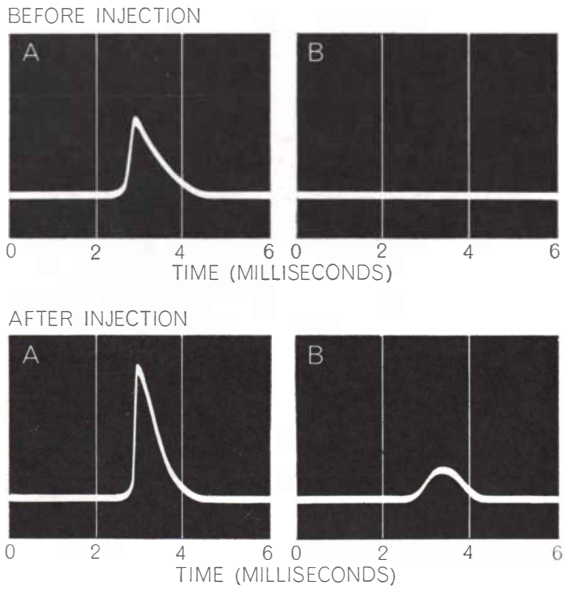
With a microelectrode it is possible to study the activity of a single nerve cell in detail either by placing the electrode near a cell to record its impulses or by pushing the electrode into the cell itself to study electrical activity across the membrane. A microelectrode within a cell reveals that the inside of the neuron is electrically polarized; it is negative in relation to the outside of the cell. When the cell is not actively discharging impulses, its negative resting potential is about 70 millivolts. Eccles showed some years ago that a stimulus applied to the afferent fibers from muscle spindles evokes in a motoneuron innervating the muscle a brief depolarization, or decrease in negative potential, that he called the excitatory postsynaptic potential. If this excitatory potential is large enough, it reaches the threshold



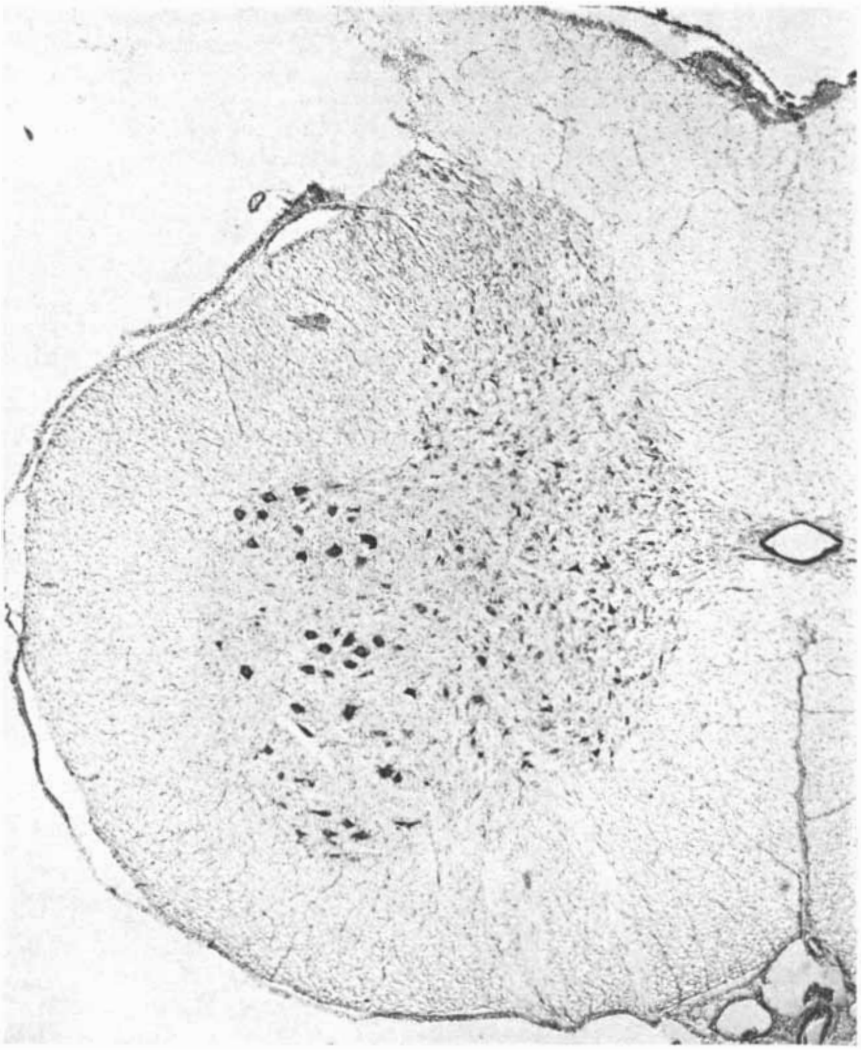




**RECURRENT INHIBITION is inhibition of motoneurons by the activity of other motoneurons. Stimulation evokes an impulse that travels into a collateral branch of motoneuron *A*, causing the discharge of impulses by a Renshaw cell (*color*), recorded near the cell (*1*). Activity at the Renshaw cell's synapses with motoneuron *B* results in an inhibitory potential, recorded intracellularly (*2*).**

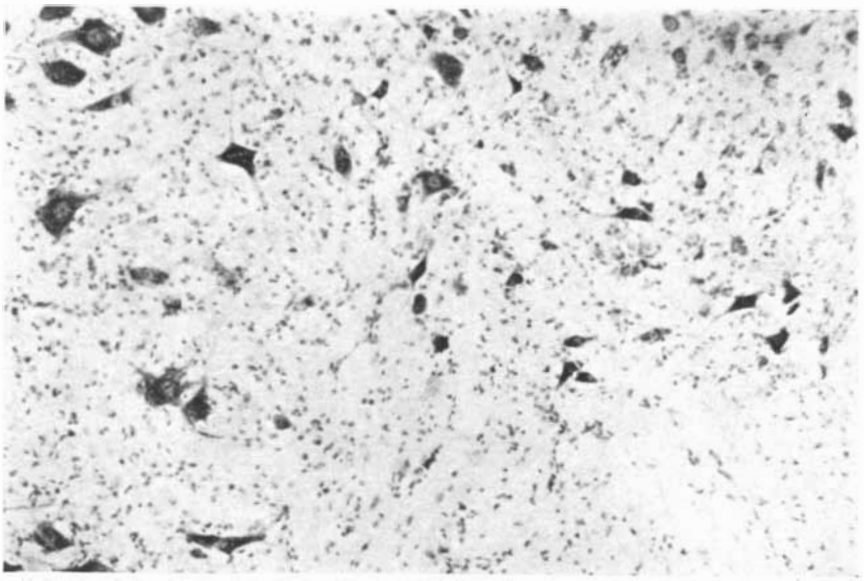



**STIMULATION of spindle afferents from one part of a muscle strongly excites motoneurons affecting that part and weakly excites motoneurons affecting another part of the muscle. The first group of cells (*A*) usually shows a reflex response whereas the other group (*B*) may not, in part because of recurrent inhibition. If the drug dihydro-beta-erythroidine, which depresses synapses of recurrent collaterals with Renshaw cells, is injected, group *B* does produce a reflex response and the response of group *A* is enhanced.**



**LOCATION OF RENSHAW CELLS was determined by R. C. Thomas and the author, who ejected a dye from a microelectrode with which they had recorded a Renshaw cell response in the spinal cord of a cat. The photomicrograph of a section of the left half of the cord, enlarged 35 diameters, shows the green dye near the ventral (*lower*) edge of the gray matter.**

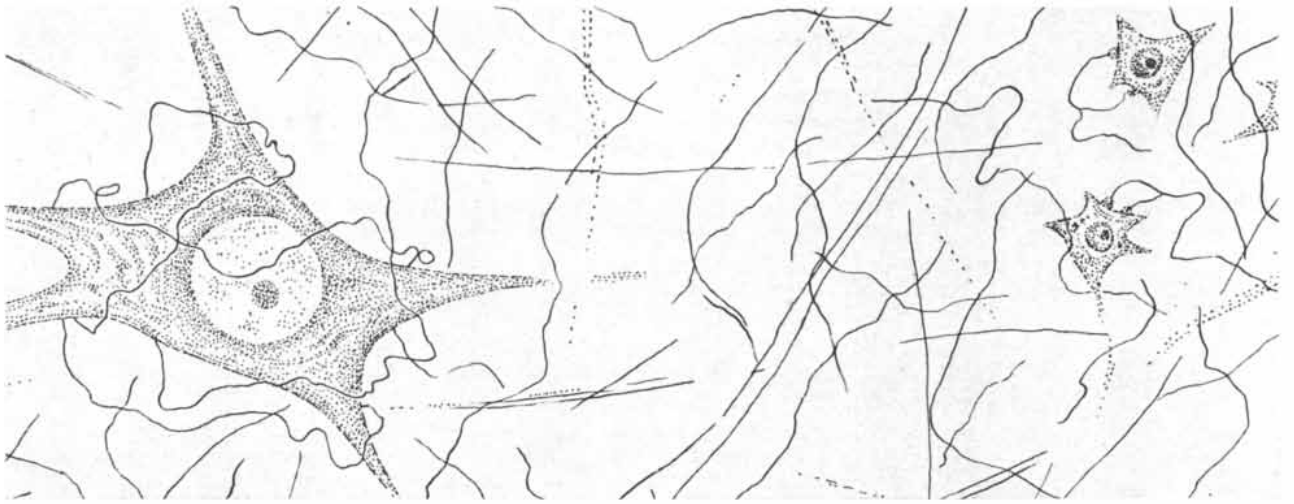


**RENSHAW CELLS may be the medium-sized neurons visible near the dye marker, enlarged about 100 diameters in this photomicrograph. The larger cells at left are motoneurons.**

level for the cell and causes an "action potential" to be discharged along the axon. The action potential is a single nerve impulse—in this case the expression in a single cell of the monosynaptic reflex. Conversely, a stimulus applied to the spindle fibers from an antagonist muscle usually results in a brief hyperpolarization, or increase in negative potential, of the motoneuron: the inhibitory postsynaptic potential [*see top illustration on page 104*].

Further studies with microelectrodes show that the important event leading to excitation or inhibition is a change in the permeability to various ions—and therefore in the conductance—of the postsynaptic membrane [see "The Synapse," by Sir John Eccles; SCIENTIFIC AMERICAN, January, 1965]. The liberation by the presynaptic fiber of an excitatory transmitter increases the permeability of sites on the postsynaptic membrane to most ions. The resulting movement of ions constitutes a current that accounts for depolarization. The liberation of inhibitory transmitter, on the other hand, increases the permeability of certain sites on the membrane only to ions under a certain size; in the motoneuron this change primarily affects chloride and potassium. The resulting inflow of negative chloride ions and outflow of positive potassium ions explains hyperpolarization. Inhibition takes place for two reasons. First, the shift in the direction of hyperpolarization directly opposes the depolarizing effect of the excitatory current. Second, the inhibitory change in permeability enables part of the excitatory current to leak out through the inhibitory synaptic sites, and the remaining excitatory current produces a smaller depolarization. The final result is that the depolarization may not reach threshold, in which case the neuron fails to discharge.

Studying the discrete changes in potential that result from the application of synchronized electric shocks to quiescent cells is a good way to learn about the precise events that take place at the synapse. One should keep in mind, however, that the situation in an active cell, subjected to continual background bombardment and responding to natural stimuli, is quite different. An oscilloscope trace from a motoneuron in the spinal cord of a cat, for example, shows a fluctuating resting potential and numerous action potentials [*see bottom illustration on page 104*]. When a withdrawal reflex is initiated by a pinch delivered to the cat's hind leg, the cell is inhibited. The stimulus reduces the fluctuations in potential, causes a general



**MOTONEURON (*left*) in a segment of the spinal cord is covered with fine fibers in this drawing based on one made by John Szentágothai at the University of Pecs in Hungary. The ventral horn of the cord had been isolated, so sensory fibers had presumably degenerated. The fine fibers, then, may be terminals of Renshaw cells, which are completely within the spinal cord segment and therefore should be intact and visible. There are no synaptic knobs on these fibers. There are knobs, however, on the fibers that synapse with smaller cells (*upper right*). These may be Renshaw cells and the knobs may be the terminals of recurrent collaterals.**

change in the direction of polarization and thus causes the cell to stop firing. Presumably the effect is the result of asynchronous activation of a number of inhibitory synapses at the motoneuron.

In 1941 Renshaw noticed that if he stimulated the axons of some motoneurons, the excitability of certain other motoneurons was reduced. Subsequent investigation, largely by Eccles' group, traced this inhibition to the branches, called recurrent collaterals, that many axons of motoneurons give off before they leave the gray matter of the spinal cord. The collaterals synapse with inhibitory interneurons (which have been named Renshaw cells), which in turn synapse with other motoneurons. As might be expected, the recurrent branches of motor axons excite Renshaw cells by liberating the same transmitter substance the main branches of the same axons liberate at the nerve-muscle junction: acetylcholine. The synapse between recurrent branches and Renshaw cells is the only one in the central nervous system for which the excitatory transmitter has been identified.

The chain of events in this kind of inhibition, called recurrent inhibition, can be initiated by the electrical stimulation of a bundle of motoneuron axons [*see upper illustration on page 105*]. The stimulus evokes in the axons an action potential that is conducted along the collaterals and that releases acetylcholine at their terminals. This causes the depolarization of Renshaw cells, which respond to a single stimulus with a burst of high-frequency impulses. That burst in turn causes the release of inhibitory transmitter at the terminals of the Renshaw cell axon. An electrode inside a motoneuron subjected to this inhibitory input records an inhibitory potential that may last as long as 50 milliseconds, the duration probably being a result of the considerable number of impulses that prompt it. A clue to the nature of the inhibitory transmitter at this synapse is the fact that its action—like that of the transmitter at all other known postsynaptic inhibitory synapses in the mammalian spinal cord—is blocked either by strychnine or by tetanus toxin.

Recurrent inhibition is apparently a form of negative feedback, since it is an inhibition of some cells as a result of the activity of other cells in the vicinity. Its functional meaning, however, is not clear, and it may indeed serve more than one purpose. Vernon Brooks and I have been able to show that it acts to suppress weak "fringe" motoneuron activity [*see lower illustration on page 105*]. By doing so it helps to localize reflexes and thus presumably helps in the execution of fine movements.

According to Eccles' postulate, inhibitory neurons should exert an inhibitory action on all cells with which they form synapses. (This can be difficult to test, since it is often impossible to know where all the branches of an axon of a cell in the central nervous system end.) A possible difficulty with Eccles' postulate is the fact that a stimulus that produces recurrent inhibition of some cells can increase the excitability of other motoneuron groups, that is, it can produce a "recurrent facilitation." Work in our laboratory implicated Renshaw cells in this apparent excitatory effect. We soon found, however, that recurrent facilitation is in fact due to the inhibition of inhibition, or "disinhibition," a phenomenon that had been demonstrated in the lateral eye of the horseshoe crab by H. K. Hartline and Floyd Ratliff of the Rockefeller Institute in 1957. The motoneurons are evidently subjected to steady background inhibition by the activity of some unidentified inhibitory cells, and Renshaw cells forming synapses with these inhibitory neurons depress their activity and release the motoneurons from inhibition [*see illustration on page 109*].

This explanation is supported by physiological and pharmacological evidence. First, the changes in membrane potential associated with recurrent facilitation seem to be caused by changes in permeability of the kind that take place at inhibitory rather than excitatory synapses. Second, strychnine and tetanus toxin, which block spinal postsynaptic inhibition but not excitation, block recurrent facilitation. All known actions of Renshaw cells, then, are in agreement with Eccles' postulate. We have found, moreover, that Renshaw cells can themselves be inhibited by various means, and this applies to other inhibitory neurons as well. Obviously the regulation of nervous discharges involves a complex variety of interactions of excitatory with inhibitory neurons.

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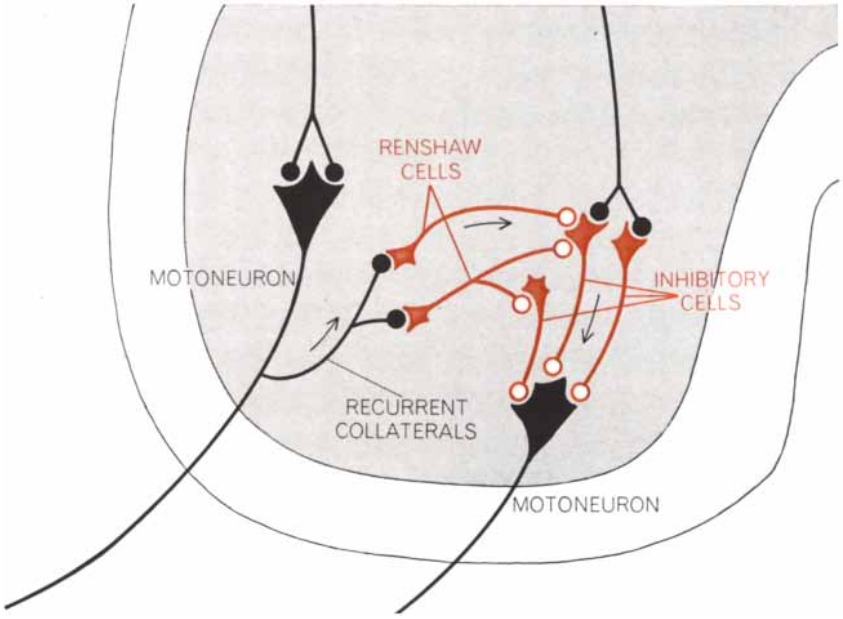
ance or the electrical properties of a cell that indicates whether it is inhibitory or excitatory. Although much is known from electrical investigations about the properties of Renshaw cells, no one has been able to identify particular structures as Renshaw cells with any degree of certainty. By ejecting a dye from the electrode with which we had recorded Renshaw cell activity we were able to determine only that these cells must be among the smaller neurons in the spinal cord's ventral horn, near the site at which motoneuron fibers leave the gray matter [*see illustrations on page 106*].

Again, although it is clear that inhibitory and excitatory terminals differ in the chemical transmitters they produce, it is not at all clear how—or indeed whether or not—they differ structurally. John Szentágothai, formerly of the University of Pecs in Hungary, has attempted to identify the structural properties of inhibitory terminals by microscopic examination of specially prepared spinal cord sections. He isolates the ventral horn of some segments of spinal cord in such a way that the blood supply is preserved although nerve axons entering the horn are cut. Thus separated from their cell bodies, axon terminals that form synapses with motoneurons should degenerate and no longer be visible—except for the inhibitory terminals of Renshaw cells, which are interneurons and should remain intact. When such a section is inspected under a microscope, only a fine meshwork of fibers is seen on and around the motoneurons; these are presumably Renshaw cell terminals. Typical terminal knobs are visible on small cell bodies in the field of view; these may be terminals of recurrent collaterals on Renshaw cells [*see illustration on page 107*].

There have been other attempts to distinguish inhibitory from excitatory terminals. Electron micrographs suggest that the regions of apposition between presynaptic and postsynaptic structures fall into two broad categories, and it has been suggested that one type of synaptic contact may be excitatory, the other inhibitory. Among the difficulties with this proposal are the observations that the same presynaptic fiber can form both types of contact and that some contacts seem to be intermediate between the two categories. Still, the possibility remains that excitatory and inhibitory synapses may be distinguishable on the basis of structure.

The properties of postsynaptic inhibition differ even in various parts of the central nervous system of the same species. The inhibitory transmitter that

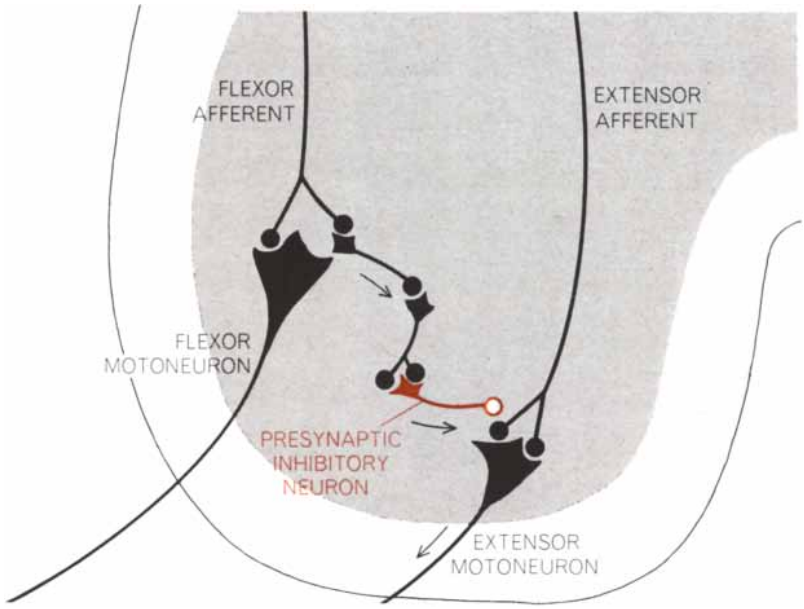



**INHIBITION OF INHIBITION produces "facilitation." There are inhibitory cells, as yet unidentified, that inhibit motoneurons. If these cells are in turn inhibited by Renshaw cells, the motoneurons become released from inhibition and appear to be facilitated.**

functions in certain parts of the brain, for example, is not blocked by strychnine, which suggests that a different substance is involved there than in the spinal cord. Again, the simplest inhibitory potential recorded in the brain may often be much longer than spinal inhibitory potentials. Nevertheless, the basic phenomenon—the inhibitory action resulting from increased permeability to certain ions—is seen in many tissues in many animals, including the brain of the snail, the muscles of crustaceans and the heart muscle as well as the central nervous system of vertebrates.

The idea that inhibition might occur "upstream" from the inhibited cell—that some presynaptic interaction could decrease the ultimate response of the system—was proposed some time ago. One important observation that pointed to such a possibility was made by Karl Frank and M. G. F. Fuortes of the National Institutes of Health in 1957. They found that stimulating certain afferent fibers could reduce the excitatory postsynaptic potential in a motoneuron—the response of the motoneuron to a test input—without there being any measurable change in the inhibited cell's membrane; unlike the usual inhibitory input, this one did not seem to hyperpolarize the postsynaptic membrane. It was recognized that postsynaptic inhibitory action could be taking place too far out on the dendritic branches of the inhibited cell to be recorded by their microelectrode and also that the inhibitory stimulus could be blocking some of the excitatory input presynaptically, preventing it from ever reaching the cell. It is now clear that distant interactions on dendrites do take place, but an important result of the work of Frank and Fuortes has been a series of studies of presynaptic inhibition, particularly by Eccles and his colleagues at the Australian National University and by Patrick D. Wall at the Massachusetts Institute of Technology.

Presynaptic inhibition in the spinal cord is revealed, like postsynaptic inhibition, by a decrease in the size of the monosynaptic reflex. One way to study its properties is to measure the excitability, or level of polarization, of the sensory terminals that carry impulses to motoneurons. This can be done by stimulating these terminals with a microelectrode placed near them, a technique developed by Wall. In this way it has been shown that impulses in some nerves can depolarize the presynaptic terminals of other nerves. Eccles' group has measured such depolarizations with microelectrodes inside the sensory axons at some distance from their terminals. When a fiber is somewhat depolarized, the nerve impulse traveling along the fiber is smaller than normal. When this smaller impulse arrives at the synapse, it causes the liberation of less than the normal amount of excitatory transmitter and thus has a smaller excitatory effect. It




**PRESYNAPTIC INHIBITION involves synapses between two axon terminals rather than between a terminal and a cell body or dendrite. It appears that afferent fibers from a flexor can excite a chain of excitatory neurons that activate a presynaptic inhibitory cell (*color*) whose terminals synapse with the excitatory terminals affecting an extensor motoneuron.**

therefore appears that presynaptic inhibition acts by depolarizing the terminals of afferent fibers, reducing their input to the next cells in the chain of transmission. It seems likely that presynaptic inhibition involves special neural pathways, the last cell of which forms synapses with the presynaptic terminals of other cells [*see illustration above*]. There is evidence from electron micrographs that such axon-to-axon synapses do exist in the central nervous system.

The last cell in the presynaptic inhibitory pathway is apparently different from the cells that carry out postsynaptic inhibition; according to Eccles, it liberates a different transmitter. Agents, such as strychnine, that block postsynaptic inhibition in the spinal cord do not affect presynaptic inhibition. Conversely, the convulsant drug picrotoxin reduces presynaptic—but not postsynaptic—inhibition. Whatever the transmitter is, it evidently acts by producing a change in the permeability of the terminal membrane. Usually the ensuing depolarization does not reach threshold and acts only to decrease the amplitude of impulses traveling along the terminals. Sometimes, however, the depolarization is large enough to reach threshold and initiate an impulse of its own; such impulses travel along the terminal in both directions and can be detected. They have no obvious functional meaning and probably do not occur to a significant extent under natural conditions, but their presence is additional evidence of the way in which presynaptic inhibition is accomplished.

In the vertebrate central nervous system presynaptic inhibition occurs in the brain and spinal cord and in interactions between them. It is widespread at the spinal level, affecting transmission in afferent fibers from skin as well as muscle, and its function may be to suppress weak inputs that would otherwise cause unnecessary responses. Wall has found that there is a steady background level of presynaptic inhibition acting on afferent terminals that carry sensory inputs from the skin. Signals in certain afferent nerves can then increase or decrease the level of presynaptic inhibition, continually modulating the sensory input to the central nervous system.

A great deal remains to be learned about the excitatory and inhibitory processes that regulate nervous activity. It is not even universally accepted that cells can be classified as either excitatory or inhibitory; it may yet develop that different branches of one fiber, liberating the same transmitter, can inhibit one cell and excite another. The chemical structure of most transmitters remains a mystery. The precise events leading to changes in membrane permeability need to be outlined in detail. And whereas this article has dealt only with chemical synapses, there are other synapses—apparently less common in the vertebrate central nervous system—at which one cell excites or inhibits another by a purely electrical interaction.

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# TURNING A SURFACE INSIDE OUT

## Normally a sphere can be turned inside out only if it has been torn. In differential topology one assumes that the surface can be pushed through itself, but then the problem is to avoid forming a "crease"

by Anthony Phillips

The great mathematician David Hilbert once said that a mathematical theory should not be considered perfect until it could be explained clearly to the first man one met in the street. Hilbert's successors have generally despaired of living up to this standard. As mathematics becomes more specialized it is difficult for a mathematician to describe, even to his colleagues, the nature of the problems he studies. From time to time, however, research on an advanced and inaccessible mathematical topic leads to a discovery that is intuitively attractive and can be explained without oversimplification. A striking example is Stephen Smale's theorem concerning regular maps of the sphere, published in 1959.

The field in which Smale was then working—differential topology, which combines concepts from topology and calculus—is one of the more abstract domains of modern mathematics. Nevertheless, a visualization devised by the late Arnold Shapiro of Brandeis University enables us to depict a startling consequence of Smale's theorem: It is possible, from the topologist's point of view, to turn a surface such as a sphere inside out.

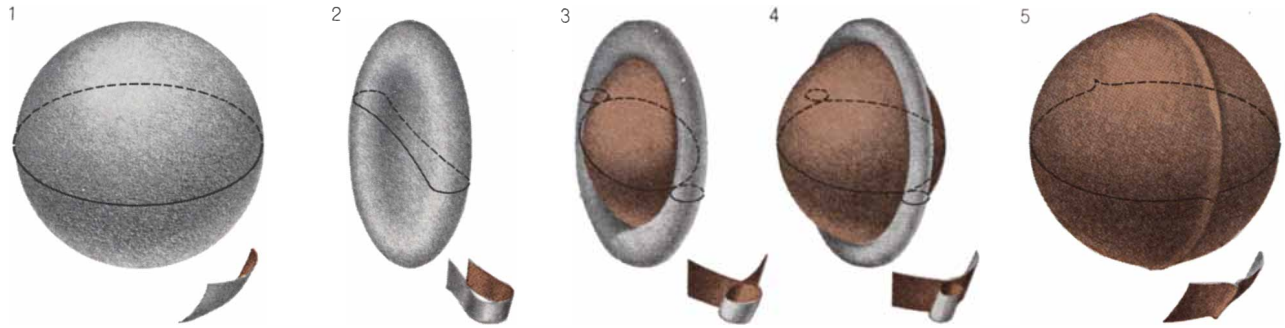
How is this accomplished? It is intuitively clear that unless a sphere is somehow torn it must remain right-side out, no matter how one is allowed to deform and displace it. If we are mentally allowed to move the surface through itself, however, so that two points on it can occupy the same point in space (this is permissible in differential topology), then a solution suggests itself. It is the deformation in which two regions of the sphere are pushed toward the center from opposite sides until they pass through each other. The original inner surface begins to protrude in two places, which are then pulled apart until the knurl—the remaining portion of the outside—vanishes. In the process, unfortunately, the knurl forms a tight loop that must be pulled through itself [*see upper illustration on opposite page*]. This results in a "crease" that is displeasing to differential topologists, whose discipline is limited to smooth surfaces.

The problem for the differential topologist is how to turn the sphere inside out without introducing a crease in getting rid of the knurl. Here too intuition indicates that the problem cannot be solved, and when Smale first announced he could prove that a solution existed, even his thesis adviser at the University of Michigan warned him that there was an "obvious counterexample" to his claim. Intuition was wrong; no fault could be found with the logic of Smale's proof. In fact, it was theoretically possible to follow the proof step by step and to discover an explicit description of the deformation that turns the sphere inside out. The argument was so complicated, however, that the actual task seemed hopeless. For some time after Smale's discovery it was known that the sphere could be turned inside out without a crease, but no one had the slightest idea how to do it.

This problem, concerning such a simple object as the sphere, was extremely mysterious and challenged the minds of many mathematicians. As far as I know the only ones who eventually worked it out were Nicolaas Kuiper, who is now at the University of Amsterdam, and Shapiro. Shapiro's idea of the deformation provides the basis for the illustration that begins at the bottom of the opposite page and ends on page 117. The deformation of the gray sphere begins with the pushing of two regions on opposite sides of the sphere toward the center and through each other so that the colored interior protrudes. The surface is then stretched, pinched and twisted through several intermediate stages too complicated to depict in their entirety. We can follow the changes between successive stages by watching what happens to ribbon-like cross sections of the surface as it is turned inside out. It is possible to understand the entire deformation by interpolating the missing parts of the surface at each stage and checking that the changes in the ribbons depicting various sections fit together coherently.

Turning a sphere inside out is only one example of the deformations shown to be possible by Smale's theorem. To explain the full implications of the theorem we must introduce mathematical definitions of the objects and deformations with which we are concerned. Let us begin with some precise descriptions of curves. The circle is defined to be the set of points in a two-dimensional plane (located by an $x$ axis and a $y$ axis) at distance 1 from the origin (the intersection of the two axes). Having established the radius as 1, we can describe any point $P$ on the circle by the angle $\theta$ between the $x$ axis and a line from the origin to $P$ [*see upper illustration on page 114*]. In other words, any point on the circle can be described by a number from 0 to 360 giving the number of degrees in the corresponding angle $\theta$.

A curve in the plane will be defined as a map from the circle into the plane. We shall consider several examples of such maps; each of them is a rule assigning to each point of the circle (or, equivalently, to each number $\theta$ between 0 and 360) a point in the plane. If $c$ is such a map, then the point it assigns to $\theta$ is denoted $c(\theta)$ and is called "the image of $\theta$ under $c$." Naturally we require that $c(0)$ equal $c(360)$,

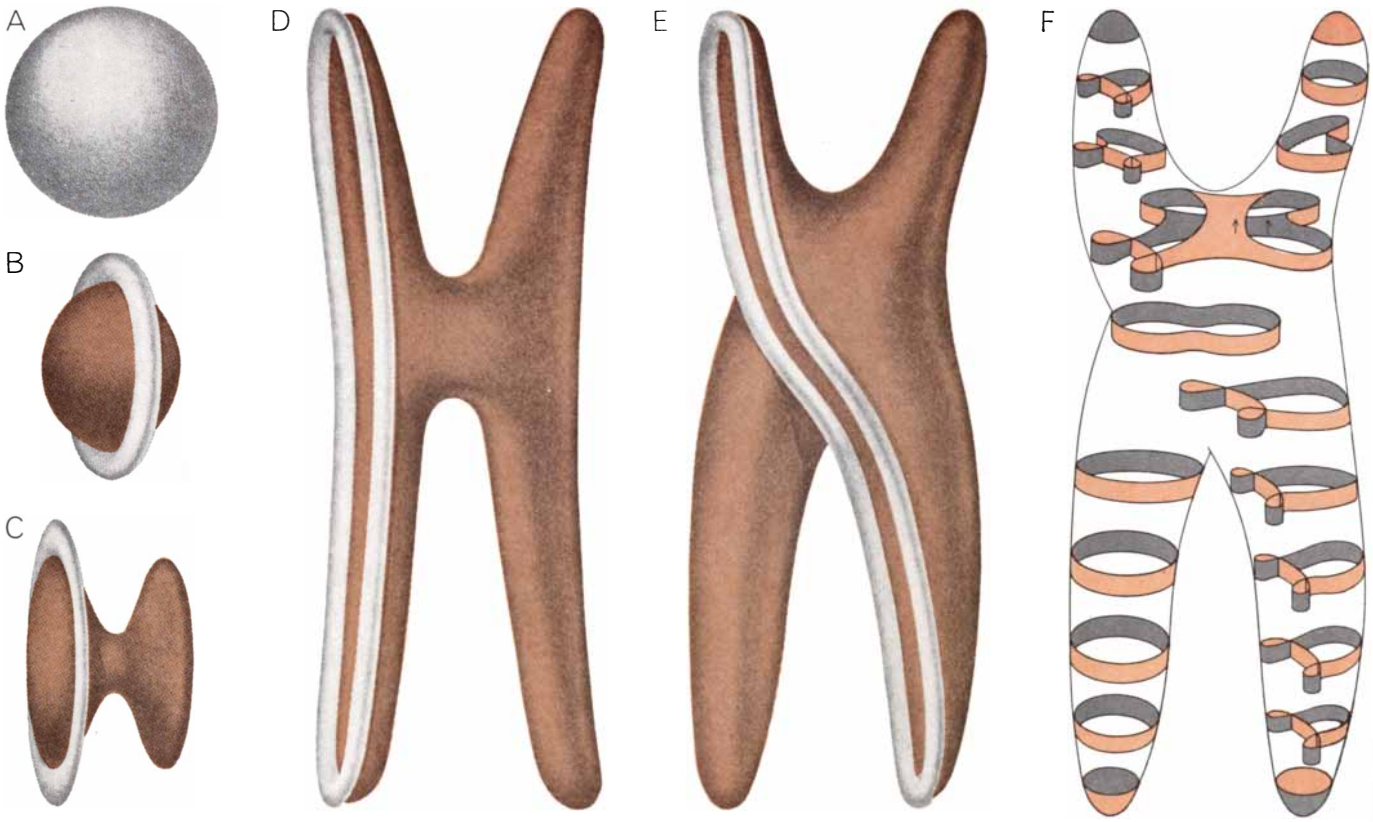



**INADMISSIBLE PROCEDURE for turning a sphere inside out entails pushing regions on opposite sides toward the center (*2*) and through each other. The original interior (*color*) begins to protrude on two sides (*3*); these two sides are pulled out to form a sphere (*4 and 5*). When the looped portion of the original surface is pulled through itself, a "crease" is introduced in the surface; this violates a law of differential topology, a discipline of mathematics that is concerned only with smooth surfaces. In this discipline moving a surface through itself is permissible. The ribbons at bottom depict a section of the surface during stages of deformation.**

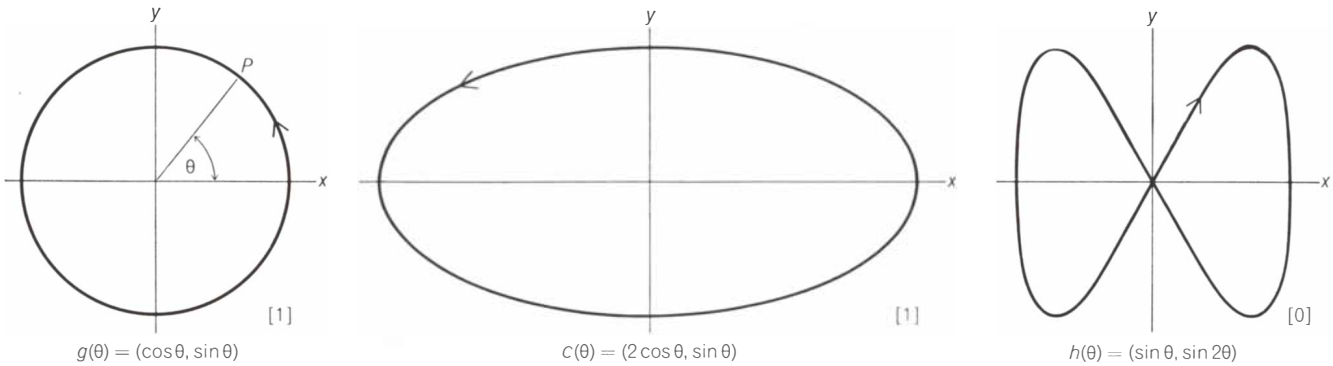
since 0 and 360 describe the same point on the circle.

Why should one give such abstract and complicated meanings to such simple terms as "curve"? There are two important reasons. First, precise definitions are essential for a sound mathematical theory. Second, a good definition will suggest by analogy how a theory can be extended to encompass new material. For example, to get a picture of a curve in the plane it is helpful to think of the path of a moving particle. This could be made into a definition more easily grasped by the intuition than "a map from the circle into the plane," but the more abstract definition will enable us to generalize our study of curves to that of two-dimensional surfaces, our main interest. A simple example of a curve is provided by the map $c$ that assigns to each $\theta$ the point in the plane with an $x$ coordinate of $2 \cos \theta$ and a $y$ coordinate of $\sin \theta$. (If $\theta$ is taken as an acute angle of a right triangle, then $\sin \theta$, the sine of $\theta$, is the ratio of the length of the opposite leg to the length of the hypotenuse; $\cos \theta$, the cosine of $\theta$, is the ratio of the length of the adjacent leg to the length of the hypotenuse.) This description can then be abbreviated to $c(\theta) = (2 \cos \theta, \sin \theta)$.

The curve defined by $g(\theta) = (\cos \theta, \sin \theta)$ is even simpler. If the point $P$ on the circle corresponds to the angle $\theta$,




**HOW TO TURN A SPHERE INSIDE OUT by steps that conform to the laws of differential topology is depicted in this illustration and those at bottom of the next four pages. The deformation begins with the pushing of opposite sides toward the center and through each other so that the interior (*color*) protrudes in two regions (*B*). One part of the original interior is then distended (*C*) to give the surface resembling a saddle on two legs (*D*). The two legs are then twisted counterclockwise to give surface *E*. This surface is shown again (*F*) with ribbons depicting it in cross section on different levels. Thin black line indicates missing parts of surface.**

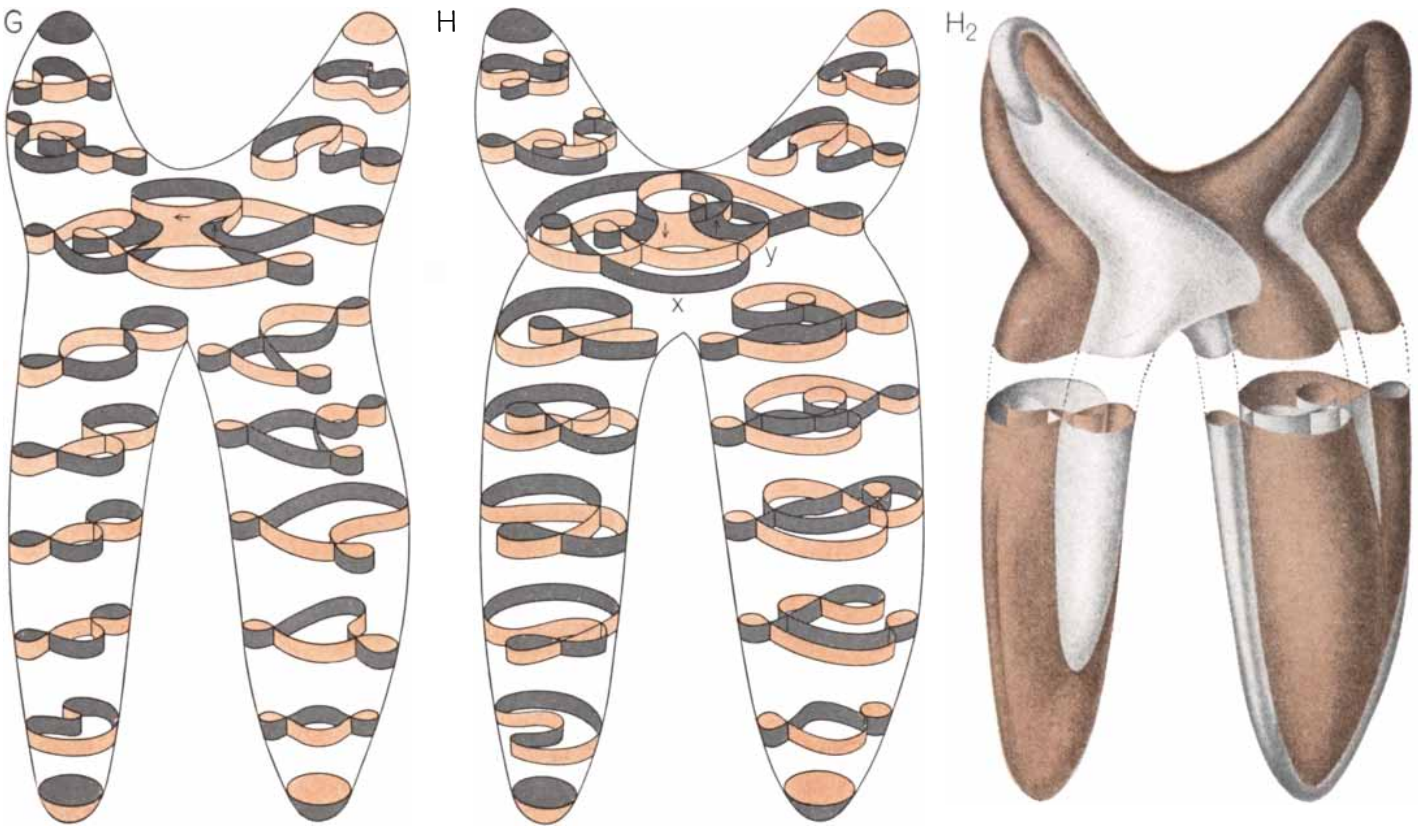



**CURVES IN THE PLANE are defined and exemplified. The circle is defined as the set of points in a two-dimensional plane at distance 1 from the origin (the intersection of the $x$ axis and the $y$ axis). A point $P$ on the circle is described by the angle $\theta$ between the $x$ axis and the line from the origin to $P$. A closed curve in the plane can be given by a map that assigns to each number $\theta$ a point in the plane. The map $c$ that assigns to each $\theta$ the point whose $x$ coordinate is given by two times the cosine of $\theta$ and whose $y$ co-**

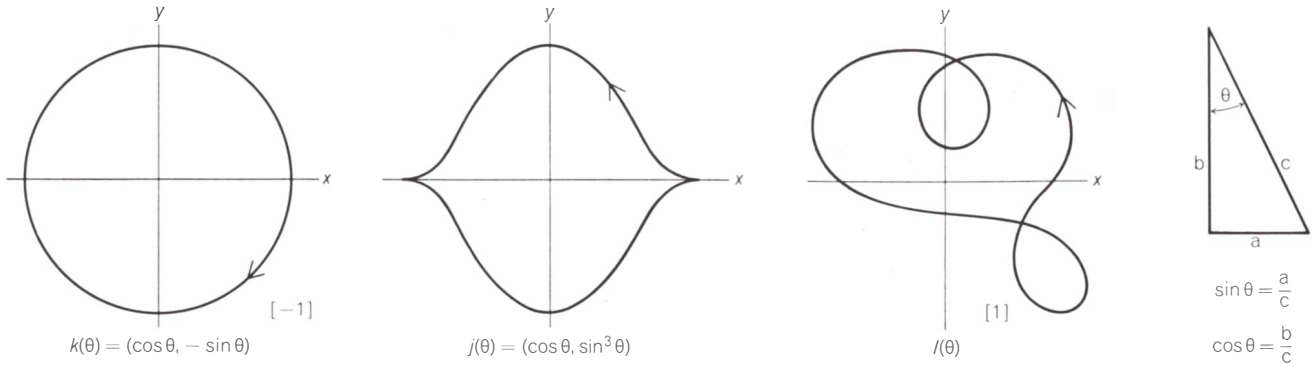
then the coordinates of $P$ itself are $\cos\theta$ and $\sin\theta$. In other words, the map $g$ assigns to each point $P$ the point $P$ once again. The map $g$ is called the standard embedding of the circle in the plane.

The curves given by the maps $c$ and $g$ are both examples of regular curves in the plane. A curve in the plane will be called regular if, as a point runs around the circle at constant speed, its image moves smoothly and with a velocity other than zero in the plane. If one represents a curve by tracing it, the motion of the pencil on the page is equivalent to the motion of the image of $\theta$ as $\theta$ runs from 0 to 360. Thus the map $l$, the image of which appears in the upper illustration on these two pages, is seen to be a regular curve but the map $j$ is not, since the pencil cannot move smoothly past a pointed end (a "cusp") without stopping.

Two regular curves are said to be regularly homotopic if one can be deformed into the other through a series of regular curves. This implies that between the two original curves there is a family of regular curves, each representing the shape of the curve at a given stage of the deformation. It can be



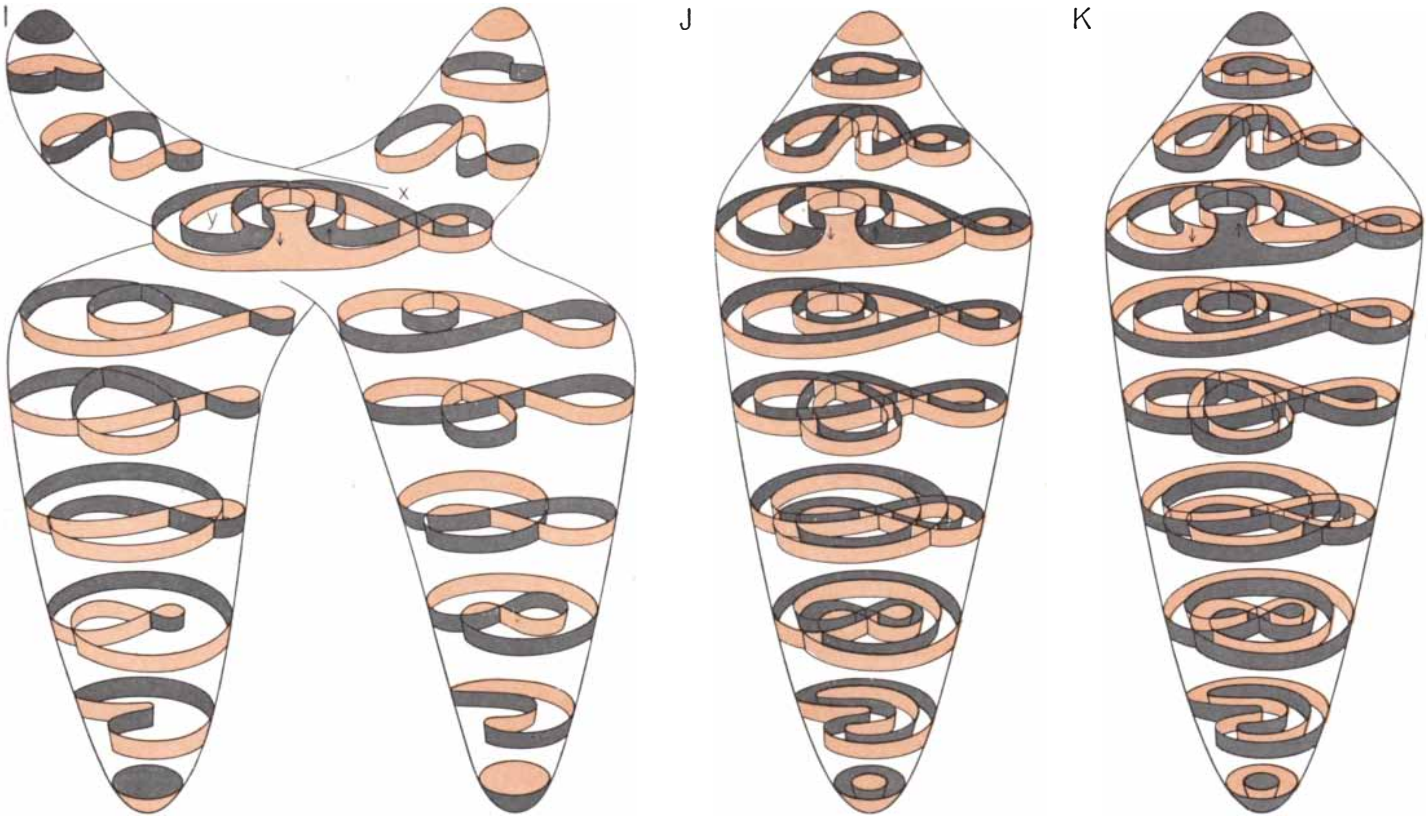

**DEFORMATION OF SPHERE IS CONTINUED here and at bottom of opposite page. Depicting the entire surface at each stage would not clarify the process; the reader must interpolate the missing parts of the surface at each stage by considering the 10 cross sections and checking that the changes at all levels fit together coherently. One stage ($H_2$) is depicted schematically so that the overall view of the surface can be borne in mind. Surface $G$ was formed by pinching and rotating the saddle of surface $F$ 90 degrees.**



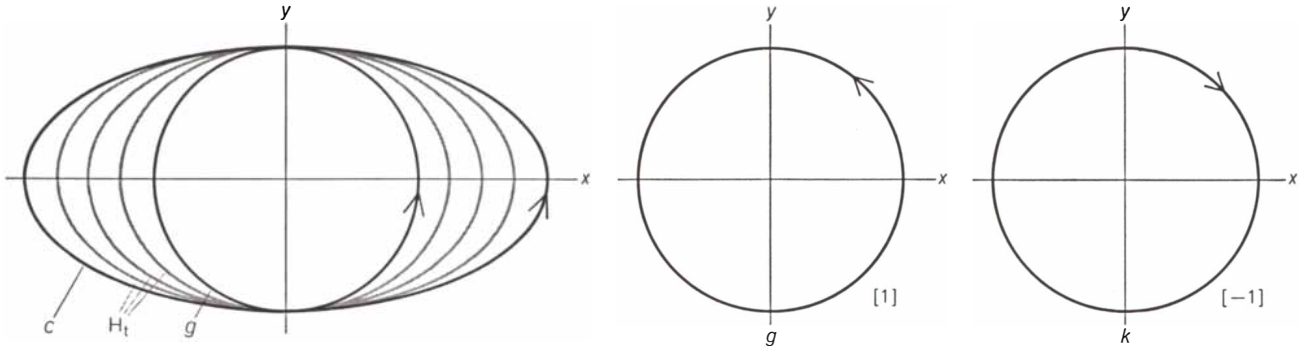

**ordinate is given by the sine of $\theta$ is written $c(\theta) = (2\cos\theta, \sin\theta)$. (Key at far right defines the trigonometric functions sine and cosine.) A closed curve in the plane is called regular if, as a pencil is traced around it, there is no "cusp," or spot at which the pencil must come to a momentary stop. (All curves in this illustration except *j* are regular.) The "winding number" listed in brackets beneath each curve gives the total number of counterclockwise turns made by the curve. Clockwise turning is counted as negative.**

demonstrated that the curves given by the maps $c$ and $g$ are regularly homotopic [*see upper illustration on next two pages*]. Here the family of curves $H_t$, or the deformation this family represents, is called a regular homotopy between $c$ and $g$.

One can show that two curves are regularly homotopic without finding the specific homotopy between them, by using the concept of "winding number." The winding number of a regular curve is the total number of counterclockwise turns the curve makes. (Clockwise turning is counted as negative, so the winding number of a curve can be negative.) The upper illustration on these two pages shows that the winding numbers of curves $g$, $h$ and $k$ are respectively 1, 0 and $-1$. It is plausible and not very difficult to prove that the winding number of a regular curve must remain fixed during a regular homotopy, so two regularly homotopic curves must have the same winding number. (It follows that no two of $g$, $h$ and $k$ can be regularly homotopic.) In 1937 Hassler Whitney, then at Harvard University, proved the more difficult converse statement: Any two regular curves with the




**REVERSAL OF COLORS, indicating a reversal of the original interior and exterior, is achieved in subsequent steps. Between stages *H* and *I* the parts of the surface marked *x* and *y* (*middle level*) move to the rear. Between *I* and *J* the two similarly shaped legs move through each other. At each level of the surface at stage *J* the cross-sectional ribbon has two gray sides facing each other. Between stages *J* and *K* the inner layer expands and the outer layer contracts, giving surface *K*, which is *J* with the colors reversed.**



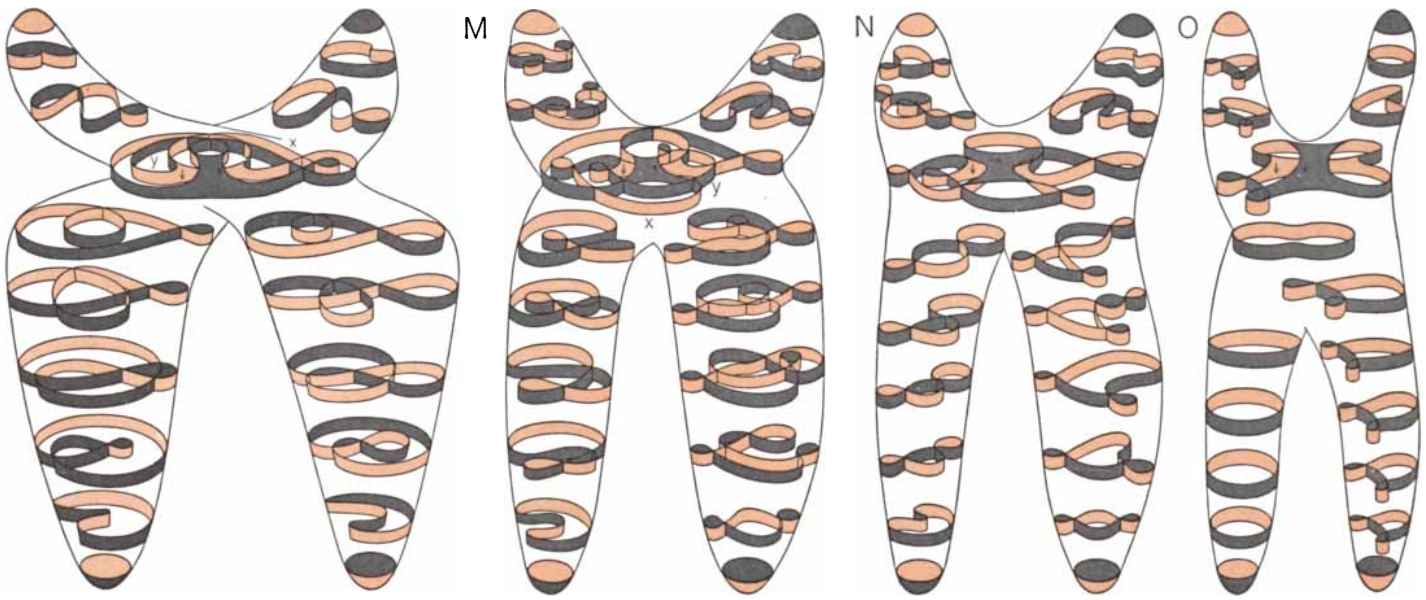

**REGULARLY HOMOTOPIC CURVES IN PLANE** can be deformed, one to the other, through a family of regular curves between them (*gray*). Thus the curves *g* and *c* are regularly homotopic, and the gray curves ($H_t$) represent successive stages of the deformation of *g* to *c*. It has been proved that only curves with the same winding number are regularly homotopic (because the wind-

same winding number are regularly homotopic. The reader may find it interesting to devise a regular homotopy between two curves with the same winding number, such as curves *g* and *l* in the upper illustration on the preceding two pages. This can be made easier with a length of chain or string. The problem is to loop the chain or string to form one of the curves, then shift it (without lifting it from the table) to form the other without introducing a cusp at any point.

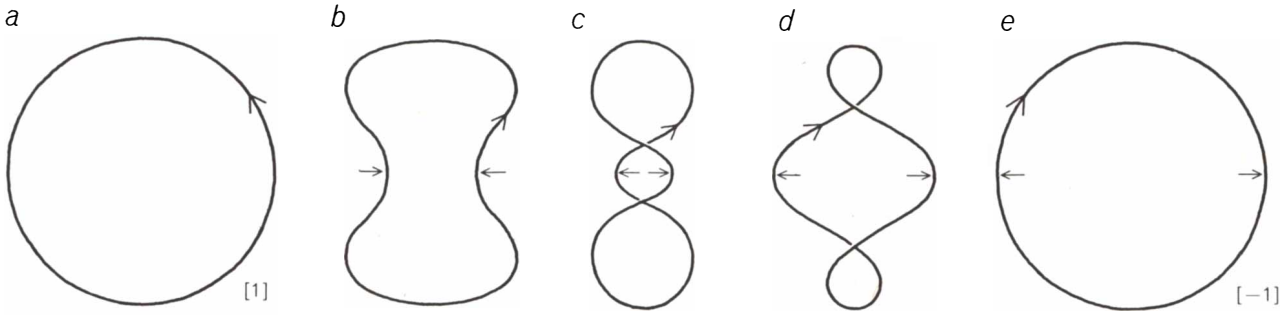
The definitions of a curve on the sphere and of a regular curve on the sphere are analogous to those of curves in the plane, the sphere being the set of points in three-dimensional space at distance 1 from the origin. Some regular curves on a sphere are shown in the top illustration on page 118. It turns out that two such curves are regularly homotopic if the parity of the number of their self-intersections is the same, that is, if they both have an odd number of self-intersections or both have an even number of them. Unlike curves on a plane, regular curves on the sphere can be regularly homotopic even if they do not have the same "winding number."

We began by defining a curve as a map from the circle into the plane. Since the circle and the sphere have analogous definitions, one is led to ask: What happens when everything is moved up one dimension? The analogue to a curve is a map from the sphere into three-dimensional space. Such a map would assign to each point of the sphere some point (its image) in three-space. An example of such a map is the standard embedding, which assigns to a point *P* of the sphere the point *P* considered as a point in three-space. This is entirely analogous to the standard embedding of the circle in the plane. Another example is the antipodal map *A* [*see bottom illustration on page 118*] that assigns to each point *P* of the sphere its diametrically opposite point *A* (*P*), considered as a point in three-space. The analogous curve is given by $a(\theta) = (-\cos\theta, -\sin\theta)$.

Suppose *c* is a curve on the sphere; thus *c* assigns to each point of the circle a point on the sphere. Since a map from the sphere into three-space assigns to each point on the sphere a point in three-space, such a map will transform *c* into a curve in three-space. This remark is the basis for the definition of the two-dimensional analogue of a regular curve: a regular map from the sphere into three-space is a map




**"BACKWARD" DEFORMATION** of the surface shown in stage *K* results in a sphere having the colored original interior as its exterior. Intermediate surface *L* corresponds to surface *I* with the colors reversed; surface *M* corresponds to surface *H*, *N* to *G*, *O* to *F*, $O_2$ to *E* and so on. The colored sphere (*surface S*) corresponds of course to the gray sphere shown as surface *A* on page 113. The en-



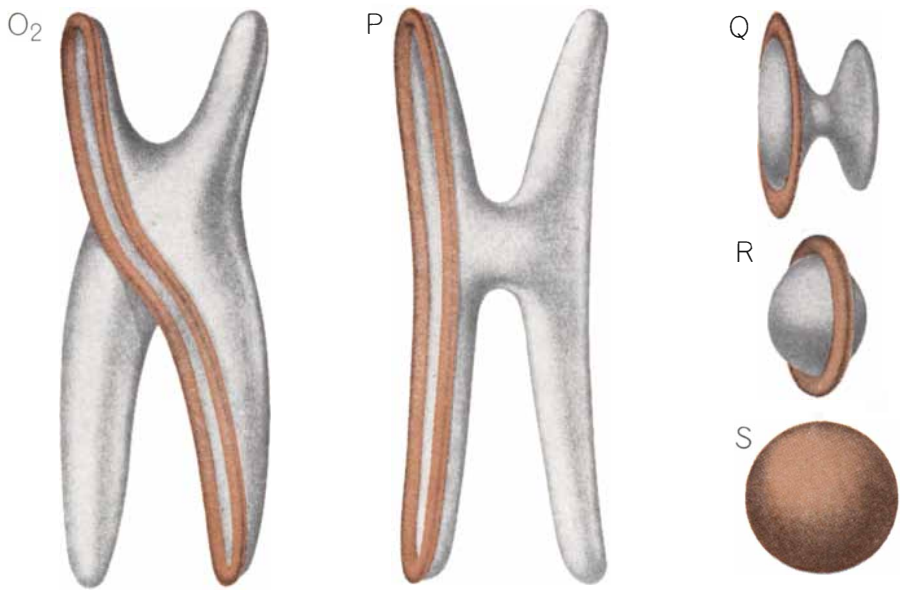

**ing number of a curve remains fixed during a regular homotopy). Thus curves *g* and *k* are not regularly homotopic. The deformation of one into the other (which is the equivalent in the plane of turning a sphere inside out) creates a change in winding number. If this deformation is duplicated with some string ("*a*" *through* "*e*") on a table, one will find it cannot be done without introducing a cusp.**

that transforms each regular curve on the sphere into a regular curve in three-space.

The standard embedding is obviously regular, and the bottom illustration on the next page shows that the antipodal map *A* transforms a regular curve into a regular curve, and that *A* is thus also a regular map. On the other hand, a sphere with a crease cannot be the image of a regular map; any curve perpendicular to the crease has a cusp.

Pursuing the analogy, we define two regular maps from the sphere into three-space as regularly homotopic if there is a family of regular maps (a regular homotopy) joining them; in other words, if one regular map can be deformed into the other through a series of regular maps. Now, we already know that the standard embedding is regularly homotopic to the antipodal map. In fact, Shapiro's visualization is of just such a regular homotopy. Since we had not yet defined regular maps when we first discussed turning the sphere inside out, we described the homotopy by showing how the images of the maps could be deformed one into the other. In retrospect it is clear that each of the surfaces in the illustrations at the bottom of pages 113 through 117 is the image of a regular map from the sphere into three-space, and that these maps can be chosen to vary smoothly and in such a way as to provide a regular homotopy between the standard embedding and the antipodal map. In particular every point on the surface designated *J* in the bottom illustration on page 115 lies opposite its antipodal point, and the deformation of *J* to *K* exchanges these points.

One big advantage of considering a homotopy of maps rather than a deformation of surfaces is that the status of self-intersections becomes logically clear. It is no longer necessary to speak of two points on the surface "occupying" the same point in space. A map from the sphere into three-space has a self-intersection when it sends two points of the sphere to the same point in space.

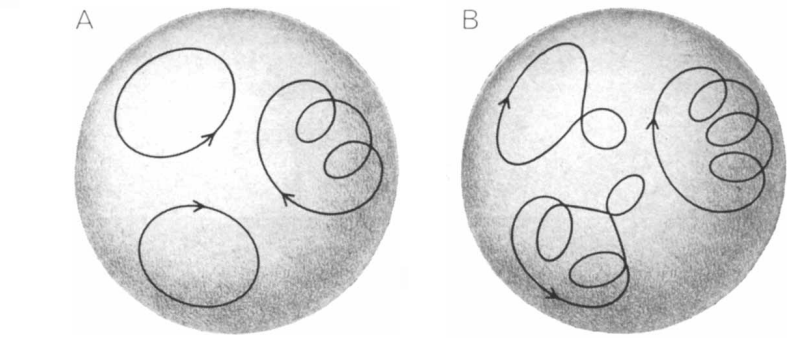



**tire deformation is accomplished without introducing a crease in the surface. The feat was first proved possible by Stephen Smale, then at the University of Michigan. The intermediate steps of the deformation were first imagined by Arnold Shapiro of Brandeis University.**

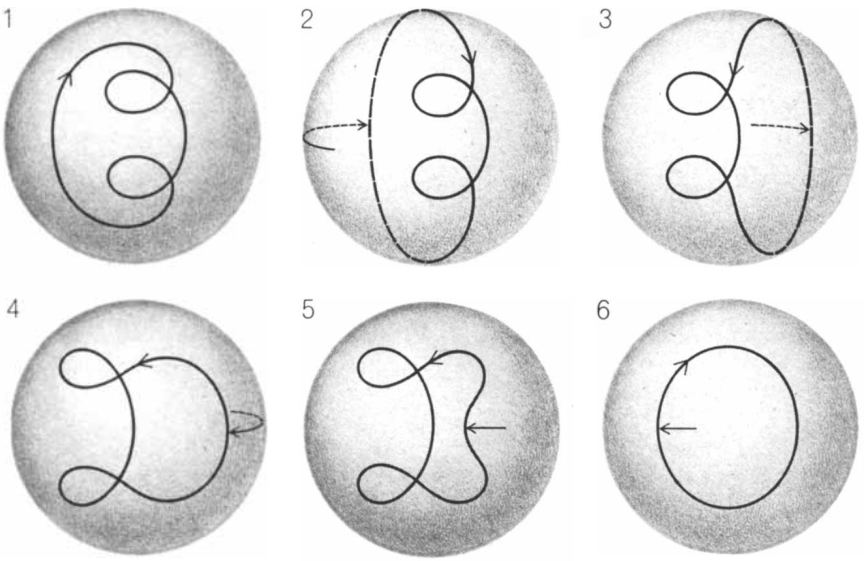
The regular homotopy between the standard embedding of the sphere and the antipodal map can be used to provide a regular homotopy that turns other simple surfaces, such as the torus, inside out. The torus is the doughnut-like surface shown in the illustration on page 119. The homotopy depicted can be described as follows. Extrude a small sphere from the surface of the torus and turn the sphere inside out. Expand the reversed sphere until it swallows the torus. A tube now leads from the outside of the reversed sphere to the inside of the torus. Enlarging this hole if necessary, pull the torus out by the inside. Shrink what remains of the sphere.

There are regular maps from the torus into three-space that are not regularly homotopic. The illustration on page 120 shows the images of four such maps, no two of which are regularly homotopic. How many such maps can there be?

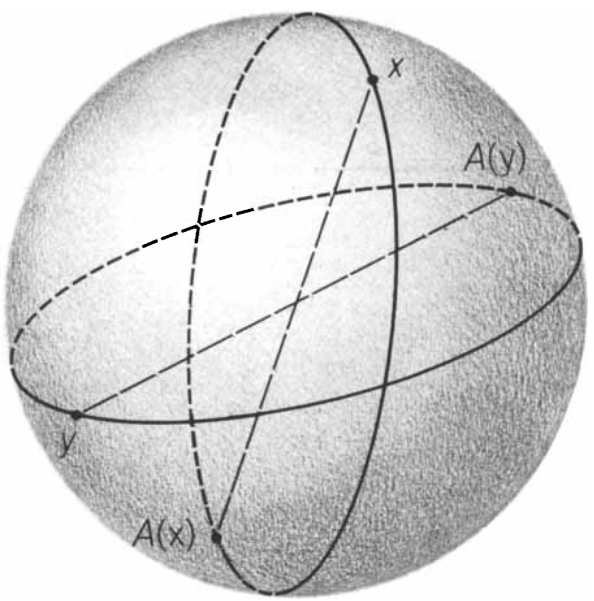
We have seen that there is an infinite collection of regular curves in the plane (one for each winding number), no two of which are regularly homotopic. We have also remarked that two regular curves on the sphere are regularly homotopic if and only if the number of their self-intersections is odd in each case or even in each case. It is therefore possible to divide all the regular curves on the sphere into two sets (those with an even number of self-intersections and those with an odd number of self-intersections) such that




**REGULAR CURVES ON THE SPHERE** can be shifted "around the back" and are not governed by rules for curves in a plane. Two regular curves on the sphere are regularly homotopic if they both have an odd or both have an even number of self-intersections. Curves on sphere *A* belong to same "regular homotopy class." Curves on sphere *B* belong to a different regular homotopy class. No curve on *A* is regularly homotopic to one on *B*.




**REGULAR HOMOTOPY ON THE SPHERE** is illustrated for two curves on sphere *A* of illustration at top. Broken segment of the curve has been shifted around the back of sphere.



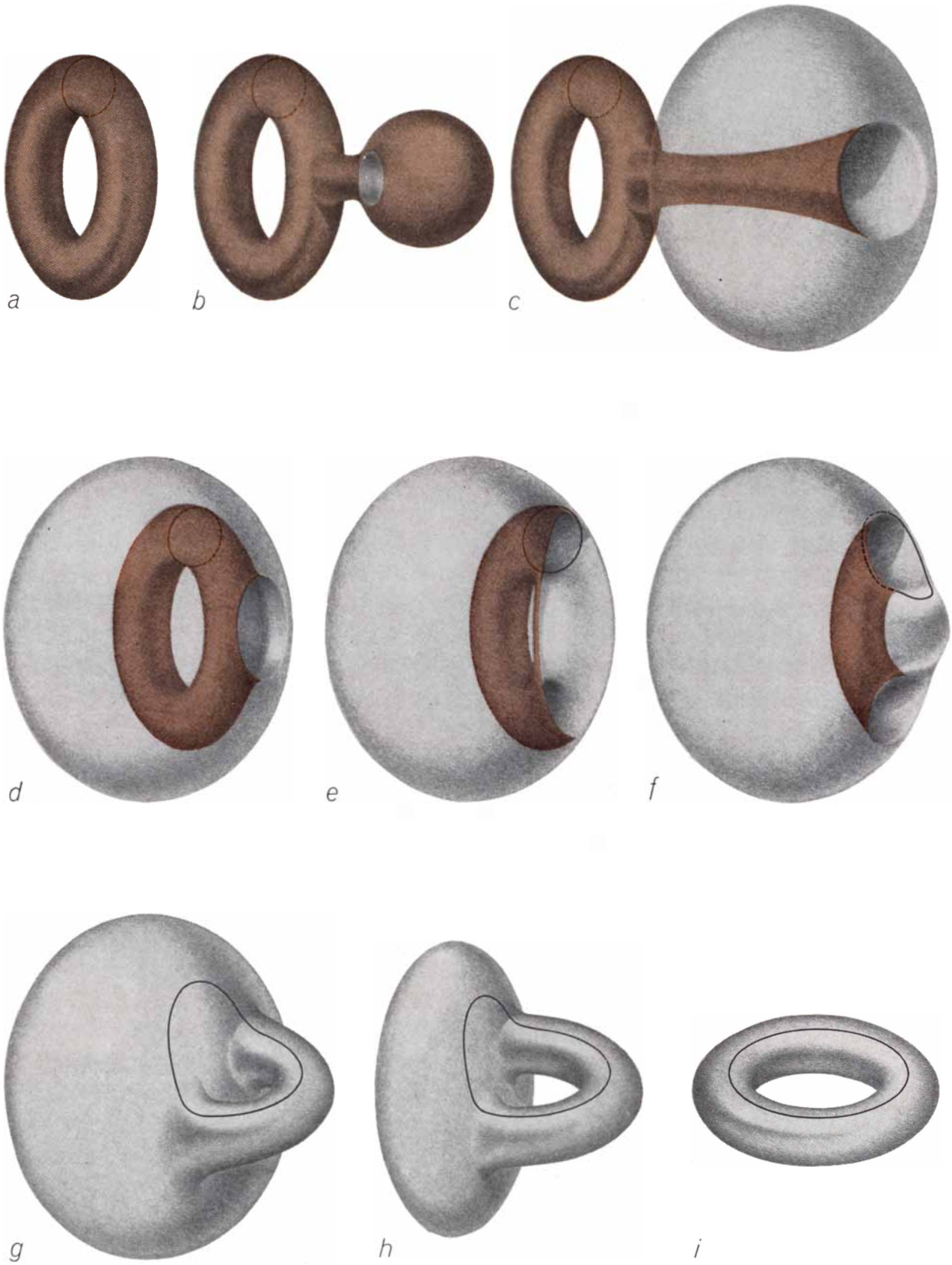

**ANTIPODAL MAP** assigns to each point on sphere its diametrically opposite point. Discovery of a regular homotopy between sphere and antipodal map proved it could be everted.

any two curves in the same set are regularly homotopic, but no curve in one set is homotopic to a curve in the other set. If we agree to call sets with these two properties "regular homotopy classes," we can state that there are infinitely many regular homotopy classes of regular curves in the plane, but only two regular homotopy classes of regular curves on the sphere.

It has been ascertained that the number of regular homotopy classes of regular maps from the torus into three-space is four. The general problem of determining the number of regular homotopy classes of regular maps from an arbitrary surface into three-space was explicitly solved only recently. The solution came as part of the extensive study of regular maps that was stimulated by Smale's research. Morris Hirsch, while a graduate student at the University of Chicago, showed in his doctoral thesis how Smale's work could be extended to regular maps of an arbitrary surface. Hirsch's work was used in turn by Ioan James of the University of Oxford and Emery Thomas of the University of California at Berkeley, who showed that the number of regular homotopy classes of regular maps from a surface into three-space depends only on a number known as the Euler characteristic of the surface, named for the great Swiss mathematician Leonhard Euler. To calculate the Euler characteristic $X$ of a surface, divide the surface into polygons. Then $X$ is given by the equation $X = P - E + V$, where $P$ is the total number of polygons, $E$ is the total number of distinct edges (each edge will belong to two polygons but should be counted only once) and $V$ is the total number of distinct vertices. It is a significant topological fact that the number thus obtained depends only on the surface and not on how the surface was divided into polygons.

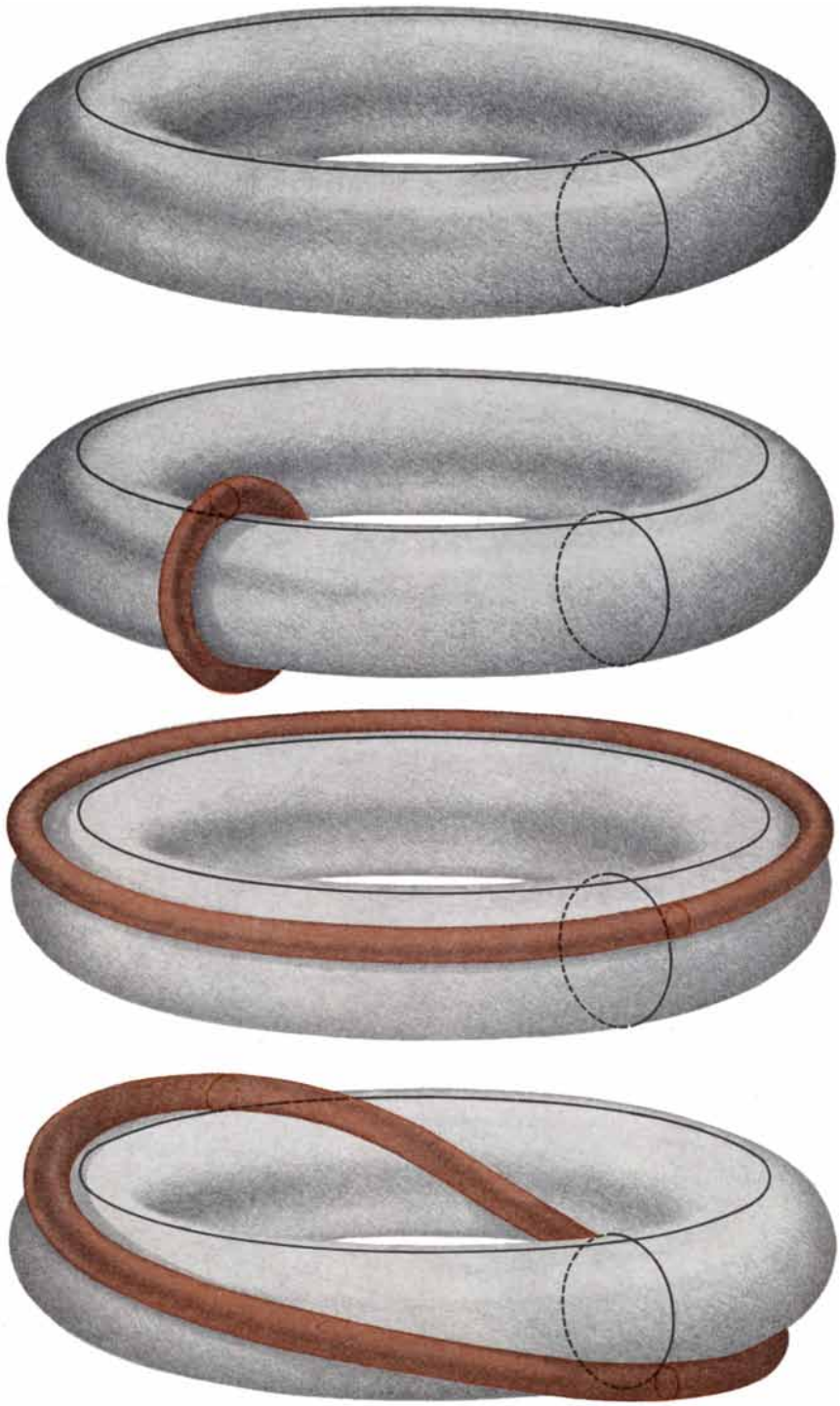
James and Thomas showed that if the Euler characteristic of a surface is $X$, then the number of regular homotopy classes of regular maps from that surface into three-space is $2^{(2-X)}$. Thus the torus (with an Euler characteristic of $X = 0$) has four distinct regular homotopy classes of maps. The sphere ($X = 2$) has only one. This is the complete statement of Smale's theorem: *Any two regular maps from the sphere into three-space are regularly homotopic.* The existence of a regular homotopy between the standard embedding and the antipodal map was only a special case.

Of course Smale's proof does not consist of drawing pictures of regular maps.




**TURNING A TORUS INSIDE OUT** involves the regular homotopy for everting the sphere. The torus is depicted with a circle designating its meridian (*a*). A small sphere is extruded from the torus (*b*) and everted (*c*). Then the inside-out sphere is enlarged until it engulfs the torus (*d*). Next the tube leading from the outside of the everted sphere to the inside of the torus is enlarged and the torus is pulled through it ("*e*," "*f*" *and* "*g*"). Finally sphere is shrunk ("*h*" *and* "*i*"). In the process the meridian has become a latitude.

In fact, Smale's paper contains no pictures at all. The intricacy of the pictures, which were in a sense implicit in Smale's abstract and analytical mathematics, is amazing. Perhaps even more amazing is the ability of mathematicians to convey these ideas to one another without relying on pictures. This ability is strikingly brought out by the history of Shapiro's description of how to turn a sphere inside out. I learned of its construction from the French topologist René Thom, who learned of it from his colleague Bernard Morin, who learned of it from Arnold Shapiro himself. Bernard Morin is blind.



NONREGULARLY HOMOTOPIC REGULAR MAPS from the torus into three-dimensional space fall into four distinct classes. This illustration shows the image of one map from each class. No two of these maps could be deformed one to the other through regular maps.

# Why is the owner of this Rover 2000 smiling?

Because he's alive.

This Rover 2000 Sports Sedan was photographed just after a head-on collision with a truck.

*With virtually any other make of car,* certain things tend to happen in these dire circumstances, among them: a) The engine tries to join you in the front seat; b) The steering column, which on most cars begins near the front wheels, competes with your chest.

Neither of these happened to the driver of this Rover 2000. (If you are wondering what *did* happen, he cracked a collar bone and two ribs because his safety harness was carelessly loose.)

## Luck Had Little To Do

Luck had very little to do with it; the answer is in the car itself.

First off, the Rover 2000 is designed with the thought that, on collision, an engine ought to go down *under* a car rather than up into your lap.

Also, the forward section of the body is designed to crumple defensively; an expensive shock-absorber, but well worth it. Note that although the front lost 18 inches, the passenger compartment is intact.

## Steering Column Has To Go

As to the lost 18 inches; in the ordinary car a foot-and-a-half of steering column has to go *somewhere*. The 2000's steering column begins behind the engine, and thus is not accident-prone. Moreover, the steering wheel is flexible and shock-absorbent.

The seats, front and back, are bucket seats of molded steel covered by fine padded leather. The tops of the front seats are padded, as well, to protect them from the faces of the rear passengers.

The top of the dash and the storage bins in front of your knees are also padded. Objects that are necessarily hard are carefully located and inoffensively shaped.

The Rover 2000 Sports Sedan is thought by many authorities to be the safest car in the world. Happily, it is also among the best handling, so that the likelihood of accident is far less to begin with, and it is fun to drive.

In addition to a revolutionary suspension system which makes for fantastic maneuverability, the 2000 also has disc brakes all around.

## Heartless To Pretend . . .

In conclusion, may we apologize for mentioning such unpleasant possibilities? However, it is even more heartless to pretend that they don't exist—and neglect to provide for them.

The stern fact is that very few cars have *any* of the safety features we have mentioned; and only the 2000 has all of them—and a good many more besides.

Oh, yes, the price: $3998. Or you can buy it for delivery in Europe and save enough to pay for your passage. If you write, we'll tell you about that, too. Thank you.

The Rover Motor Co. of N. America Ltd., Chrysler Bldg., New York

# MATHEMATICAL GAMES

## *How to "cook" a puzzle, or mathematical one-uppery*

by Martin Gardner

*Too many cooks spoil the broth.*
—Old English Proverb

When a mathematical puzzle is found to contain a major flaw—when the answer is wrong, when there is no answer or when, contrary to claims, there is more than one answer or a better answer—the puzzle is said to be "cooked." The expression was taken over from the argot of chess. (*The Oxford English Dictionary* quotes an 1899 statement about chess problems to the effect that "if there are two key-moves, a problem is cooked.")

An entire book could be written about the more amusing instances of chess problems and game analyses by experts that were later cooked by other experts. In *Curious Chess Facts* (Black Knight Press, 1937) Irving Chernev cites what is surely one of the most embarrassing chess mistakes ever to appear in print. The eighth edition of a popular late-19th-century German handbook on chess openings, by Jean Dufresne and Jacques Mieses, gave the following line of play for a queen's gambit declined. (In this notation *N* is the symbol for knight.)

| White | Black |
|---|---|
| 1. P—Q4 | P—Q4 |
| 2. P—QB4 | P—K3 |
| 3. N—QB3 | P—QB4 |
| 4. N—B3 | BP × P |
| 5. KN × P | P—K4 |
| 6. KN—N5 | P—Q5 |
| 7. N—Q5 | N—QR3 |
| 8. Q—R4 | B—Q2 |
| 9. P—K3 | N—K2 |

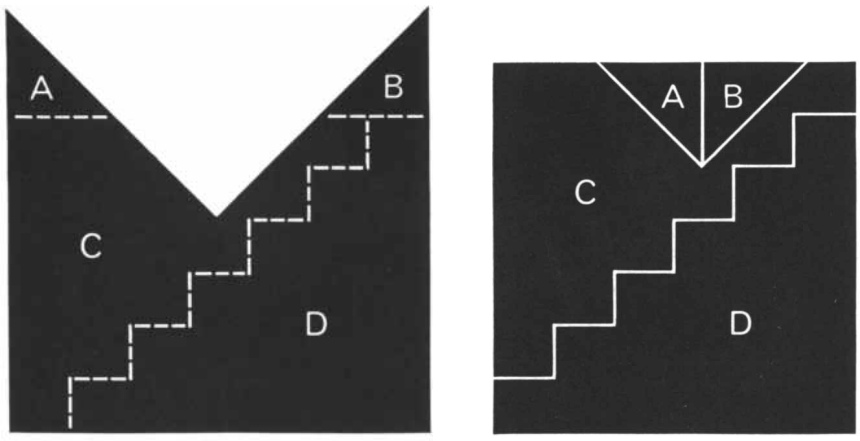
Black, the authors wrote, now has a "superior position." The fact is, however, that White can checkmate on his next move. Readers may enjoy playing to the position and seeing how quickly they can spot the mating play.

Science progresses, of course, by a never ending series of cooks. Indeed, as the philosopher Karl Popper has emphasized, a scientific theory is "empty" if there is no conceivable way to cook it; the more ways there are in which a theory might be cooked, the stronger the theory is if it ultimately passes all the tests. Mathematics is regarded as having an iron certainty not possessed by science, but mathematicians can make mistakes and so even in mathematics a proof has to be established by the social process of confirmation by others. The history of mathematics is filled with "proofs" by eminent mathematicians that were later cooked. This is particularly the case in recreational mathematics, a field dominated by amateurs.

Sam Loyd, the greatest of American puzzle inventors, published such a vast quantity of chess problems and mathematical puzzles that it is not surprising scores of his ingenious creations turned out to have fatal flaws. One of his worst mistakes was his solution to a dissection problem that is reprinted on page 27 of his *Cyclopedia of Puzzles*. The reader is asked to cut the figure shown at the left in the illustration on this page—a square missing a quarter-section—into the fewest pieces that can be rearranged to make a perfect square. Loyd's four-piece answer is shown by the broken lines in the figure at the left and the reassembled pieces are shown at the right. "There are numerous ways of performing the feat with from five to a dozen pieces," Loyd wrote, "but the answer given is both difficult and scientific."

It was the British puzzle expert Henry Ernest Dudeney, a better mathematician than Loyd, who cooked this puzzle. Packing the little triangles into the "valley" forms a rectangle, which is then presumably converted by a "stair-step" principle into a square. But the step principle does the trick only if the sides of the rectangle are in certain ratios, and the ratio in this case (three to four) is not one of them. (A formula for the ratios that do make possible application of the step method is given by Geoffrey Mott-Smith in his answer to Problem 88 in *Mathematical Puzzles* (Dover, 1954). Loyd's clever dissection produces not a square but an oblong. Dudeney presented a correct five-piece dissection [*see top illustration on opposite page*]. No solution with four pieces is believed to be possible, but Harry Lindgren, in his beautiful book *Geometric Dissections* (Van Nostrand, 1964), shows how two of the miter-shaped pieces can each be sliced in the same way into four parts and the eight pieces re-formed to make two congruent squares [*see bottom illustration on opposite page*].

Sometimes a puzzle is cooked and then the cook is cooked. Angelo Lewis, an Englishman who wrote books on magic and puzzles under the pseudonym "Professor Hoffman," gave a puzzle with 20 counters in his book *Puzzles Old and New* (1893): In the formation shown at the top of page 124,



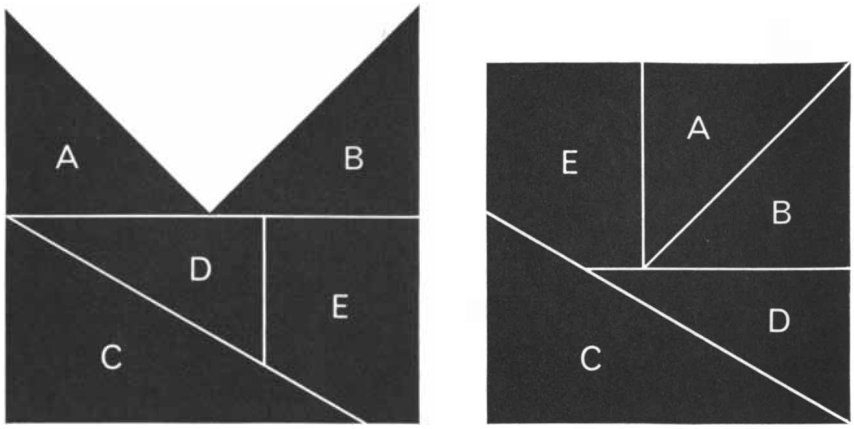

***A Loyd miter-to-square dissection that was cooked by Dudeney***

how many different squares are indicated by four counters at their corners? Seventeen, Hoffman said. In an article "The Best Puzzles with Coins" (*The Strand Magazine*, 1909) Dudeney cooked this statement by listing 19 different squares. In actuality there are 21; Dudeney gave the correct figure when he reprinted the puzzle in one of his books. The reader should have no difficulty finding the 21 squares, but the second part of this old puzzle is less easy: Remove six counters so that no square of any size remains indicated by four counters at the corners.

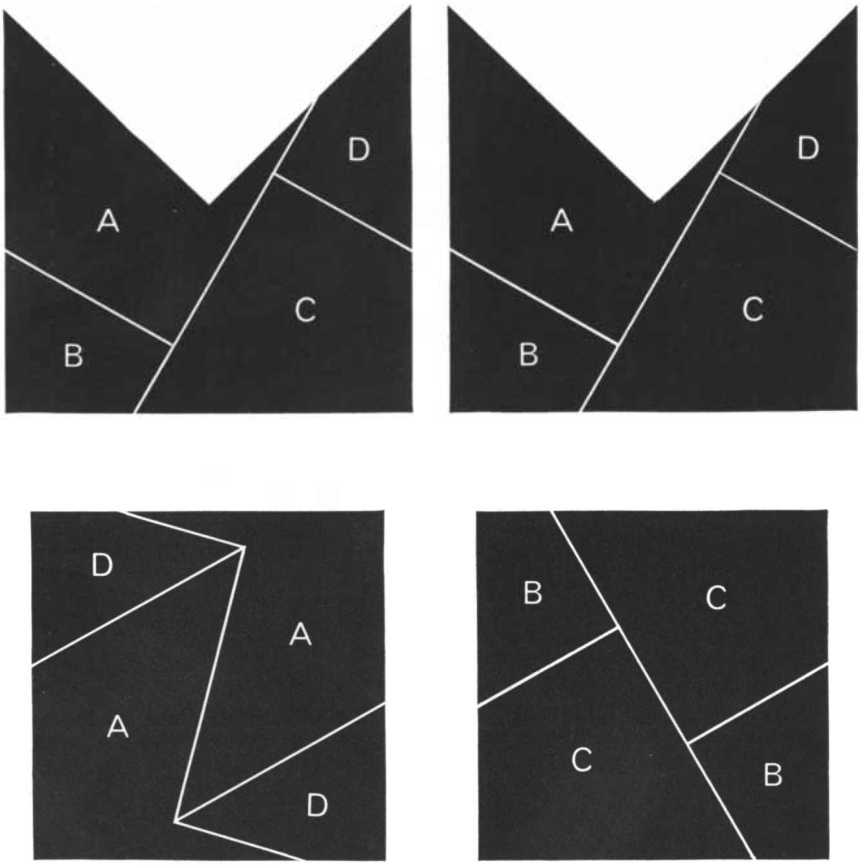
Most of Dudeney's errors were caught by readers of his magazine and newspaper columns, enabling him to correct them before the puzzles appeared in books. But even his books contain many cookable puzzles. Consider the following problem of the rook's-tour type, which appears in *Amusements in Mathematics* (Problem 244) and *Modern Puzzles* (Problem 161). A car starts at intersection *A* at the edge of a square city area seven blocks on the side [*see bottom illustration on next page*]. Alternatively, one could place a rook on the king's square of a standard chessboard, but moving along lattice lines makes the question of distance less ambiguous. The car must travel the longest route possible without making more than 15 turns and without going over any part of its path twice. In achieving the maximum distance it must also leave the fewest possible intersections unvisited.

An inferior solution [*at left in illustration*] was given in the two Dudeney books: a path of 70 blocks with 19 lattice points unvisited. Dudeney himself cooked this with the path shown in the middle picture (solution to Problem 268 in his later book, *Puzzles and Curious Problems*), which is 76 blocks long and leaves only three intersections untouched. Is this the ultimate answer? No; Victor Meally of Dublin County in Ireland recently sent me the path shown at the right in the illustration: 76 blocks, 15 turns and only *one* corner unvisited! Is it possible to cook the problem again by finding a 15-turn path longer than 76 blocks, or a 76-block path that visits *all* intersections? Probably not, but as far as I know Meally's solution has not been proved final.

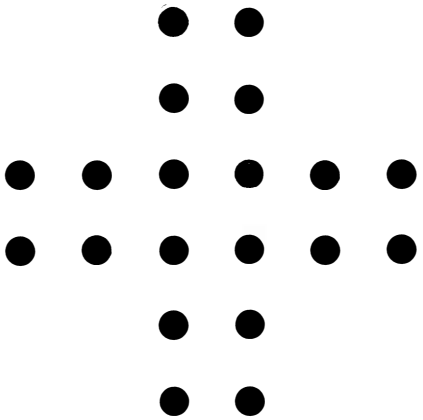
Problem 57 in *Puzzles and Curious Problems* shows a clockface with Roman numerals and asks how it can be cut into four pieces each bearing numerals that add up to 20. Since the numbers 1 through 12 add up to 78, some device must be found for raising the total to 80. Dudeney's clumsy method was to view the IX upside down as XI, making possible the dissection shown at the left in the illustration on page 127. Loyd removed this blemish by publishing (in 1909, he reports in his book *Sam Loyd and His Puzzles*) the dissection shown at the right in the illustration. Loyd in turn overlooked a dozen other equally perfect solutions, however, none of which requires that a numeral be viewed from the wrong side. The reader should be able to find nine of them without much effort, but three are quite elusive. Note that the Roman numeral for 4 is written IIII, according to the usual custom among clockmakers, rather than IV. The numerals must be regarded as being permanently attached to the rim of the clockface; that is, a dissection line may go *through* one of the hours, but it is




***Dudeney's correct five-piece dissection***




***Lindgren's dissection of two miters to two squares***



*A twice-cooked counter puzzle*

not allowed to loop *around* any numerals, separating them from the rim. If this were allowed, the problem would lose interest, because hundreds of solutions would be possible.

In editing Loyd's mammoth *Cyclopedia* for two Dover paperback collections, I found hundreds of mistakes, most of them printer's errors. (The book had been put together hastily by Loyd's son, working from clippings, after his father's death.) Among several legitimate cooks that I missed, one of the most confusing (the confusions are of the kind that must constantly plague those who keep records on artificial satellites) has to do with Loyd's eagle problem on page 117 of the *Cyclopedia* and was first called to my attention by D. H. Wheeler of Minneapolis. Exactly at sunrise an American eagle takes off from the top of the Capitol dome in Washington, flies due east until the sun is overhead and then reverses its direction and flies due west until it sees the sun set. Since the eagle and the sun move in opposite directions during the morning part of the flight and in the same direction during the afternoon part, it is clear that the afternoon flight will be longer and that the eagle will end it at a spot west of where it started. The eagle rests until sunrise and repeats the sequence—it flies east until it sees the sun at noon, flies west until it sees the sun set and then rests until the next sunrise—until it eventually works its way around the earth to Washington again. Assume that the circumference of the flight circle, from the dome around the earth on an east-west path and back to the dome, is exactly 19,500 miles. Assume also that at the end of each "day," as observed by the eagle, it ends its flight 500 miles west of where it started at sunrise. When the eagle gets back to the Capitol, how many "days" have elapsed as measured by someone in Washington? The answer 38 days, given in the first of the two paperback collections, is wrong. How does the reader calculate it?

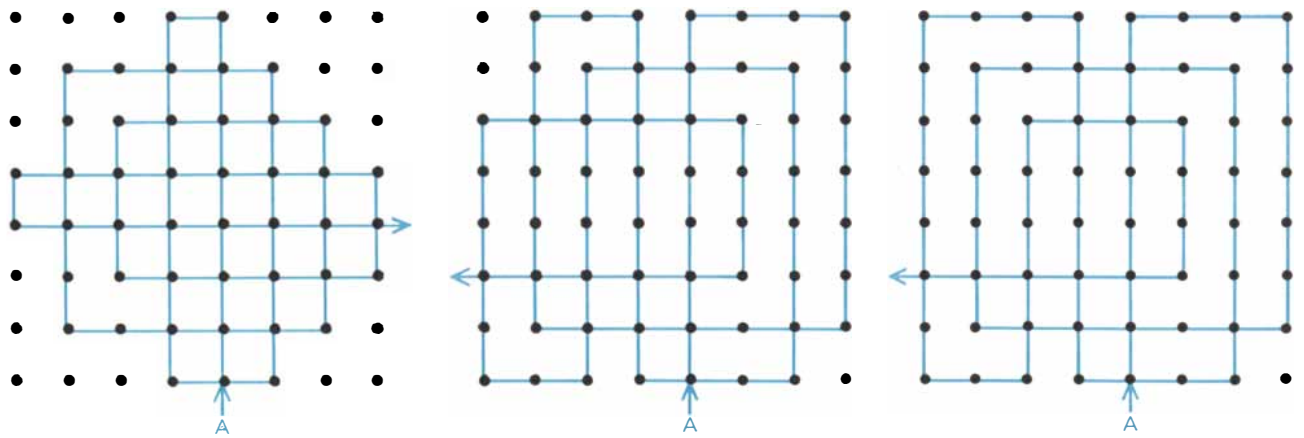
Geography is also involved in one of the most brilliant of all puzzle cooks. An explorer stands at a certain spot on the earth. Looking due south, he sees a bear 100 yards away. The bear walks 100 yards due east while the explorer stands still. The explorer then points his gun due south, fires and kills the bear. Where is the man standing? The original answer was, of course: at the North Pole. As explained in this department back in February, 1957, however, the problem has another answer. The man could be standing very close to the South Pole—so close that when the bear walks east, the 100-yard path carries it once around the pole and back to where it started. Actually there is an infinite set of answers of this type, because the man could stand still closer to the South Pole, allowing the bear to circle the pole twice, or three times, and so on. Is the problem now completely cooked? Far from it. Benjamin L. Schwartz, writing in a mathematics journal six years ago, found two more completely different families of solutions! Read the problem again carefully and see if you can think of them.

In addition to genuine cooks of problems in this department, I also sometimes receive from astute readers what, for want of a better name, I call the quibble-cook. This is a cook that takes advantage of a play on words, or a lack of precision in stating a problem's conditions. They are often quite amusing. I once wrote that if a network has more than two vertices where an odd number of lines meet, it is impossible to draw the figure without taking the pencil off the paper or retracing any part of the path. Someone wrote to tell me that he owned a pencil with a retractable point. He could draw part of a network, retract the point, then continue moving the pencil along a previously drawn line without "retracing" it or "taking the pencil off the paper" until he was ready to press a button and push the point out again. With this technique he could, of course, draw any kind of network under the given conditions.

I once gave this joke problem in a children's book. Circle six digits in the following table so that the total of circled numbers is 21:

| | | |
|---|---|---|
| 9 | 9 | 9 |
| 5 | 5 | 5 |
| 3 | 3 | 3 |
| 1 | 1 | 1 |

My answer was to turn the page up-




*First solution to a graph puzzle* (left) *and two cooks*

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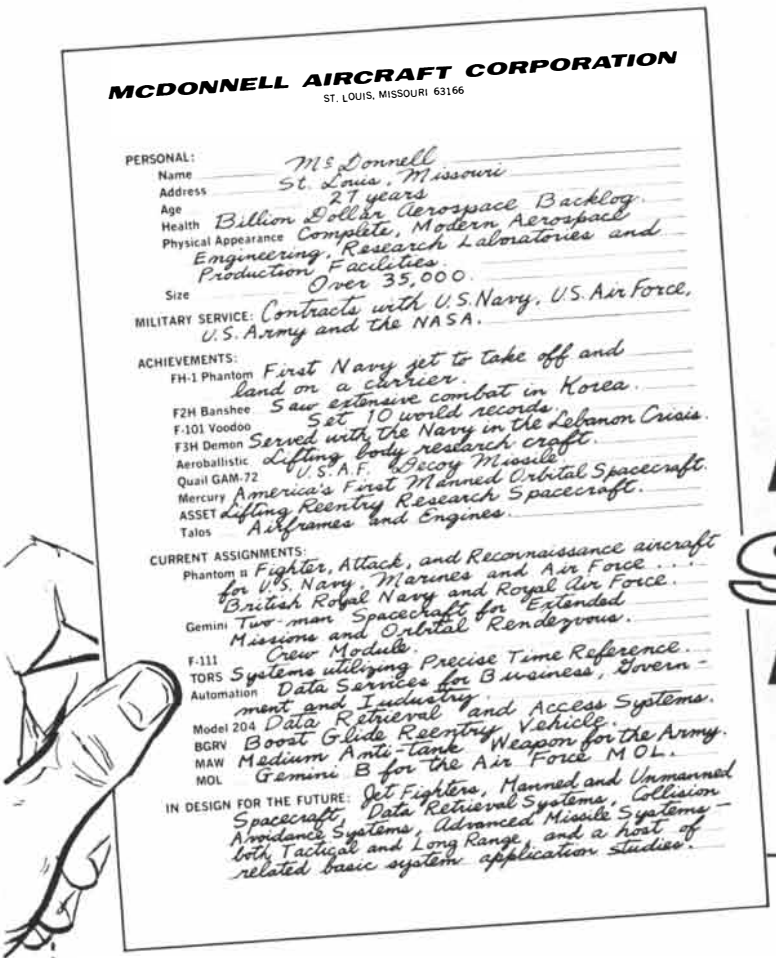


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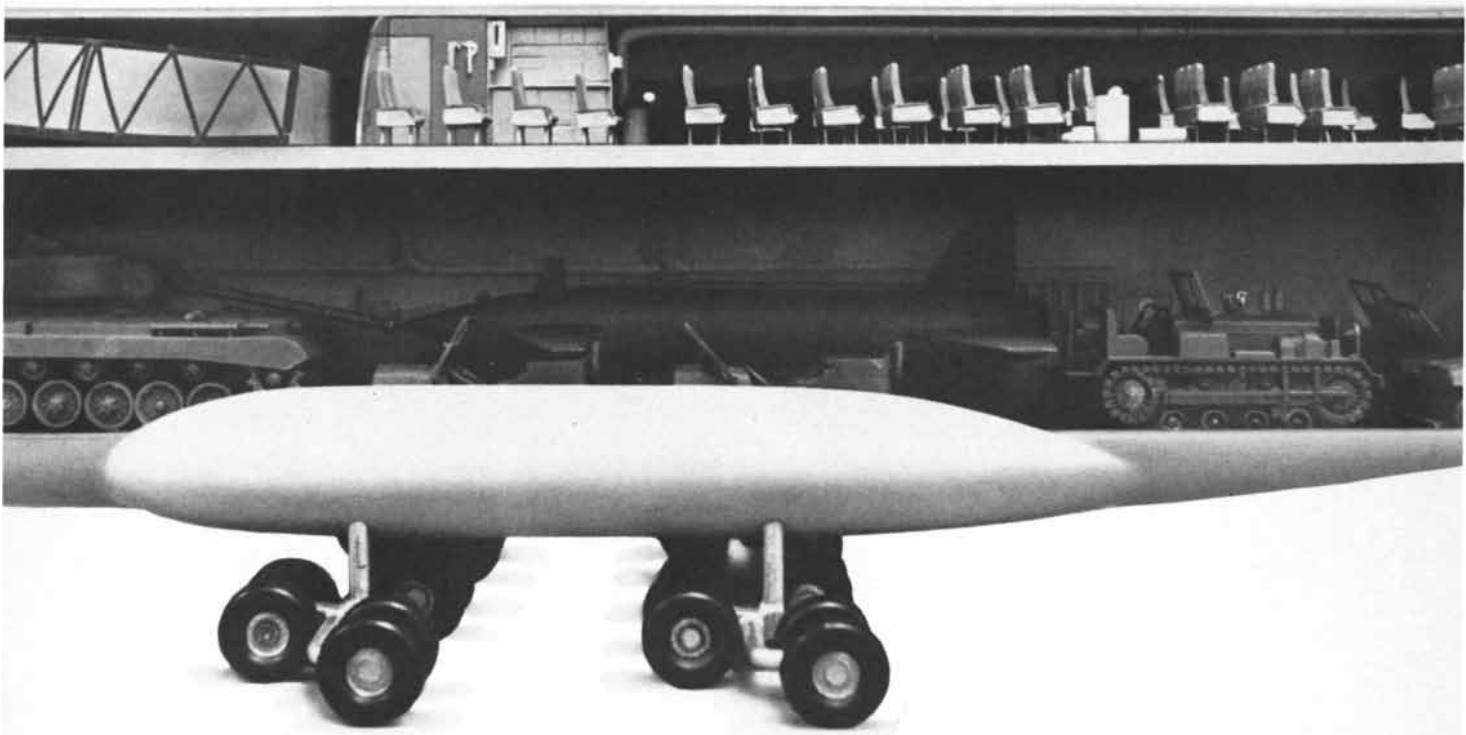
## YOU HAD TO MISS THE FIRST PASSENGER PLANE

## BUT YOU DON'T HAVE TO MISS THE C-5A



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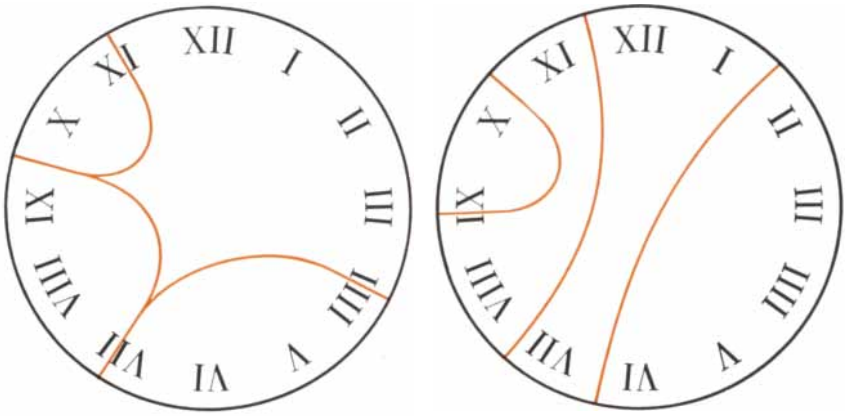


*Dudeney's clock-puzzle answer* (left) *and Loyd's cook* (right)

side down, circle each of the three 6's and each of the three 1's. Howard R. Wilkerson of Silver Spring, Md., delightfully quibble-cooked this problem by finding a much better solution. Without inverting the page he circled each of the 3's, circled the 1 on the left and then drew one larger circle around the other two 1's. The sum of the circled numbers, 3, 3, 3, 1, 11, obviously is 21.

Last month's problem was to interpret a wood engraving called "Three Spheres" by the Dutch graphic artist Maurits C. Escher. It is a picture of three flat disks, each painted to simulate a sphere. The bottom disk is flat on a table. The middle disk is bent at right angles along a diameter. The top disk stands vertically on the horizontal half of the middle one. Clues are provided by a fold line in the middle disk and by identical shading on the three pseudospheres.

I promised in the February issue to report on the best solutions from readers of an unsolved "isometric solitaire" problem. Fifteen pennies are arranged in triangular formation. One penny is removed and then jumps are made as in checkers except that the triangular lattice allows jumps in six different directions. A chain of jumps is considered one "move," and the task is to jump all but one coin in the fewest moves. Only jumps are allowed; several readers failed to realize this and sent solutions containing illegal nonjump moves.

Nine moves seems to be the minimum. Friend H. Kierstead, Jr., of Cuyahoga Falls, Ohio, A. B. Hersey of Arlington, Va., and Edouard Marmier of Zurich sent informal proofs that nine is minimal, but in the light of this month's topic and the fact that other readers sent impressive proofs that 10 is the minimum I hesitate to vouch for their accuracy. By April 1, 97 readers had found nine-move solutions of widely varying types. All of them start with a vacancy in the middle of a side, so it is probable that no solutions exist in which the starting hole is at any other spot. Most of the solutions end with the single coin on the spot that was initially vacant.

Since it is not possible to list the names of all nine-move solvers, I searched for some unusual aspect of the solutions that would yield a smaller set of names. The following readers sent nine-move solutions that end with a dramatic five-jump sweep at the finish: E. S. Ainley, Mrs. Stephen Bower, B. N. Carr, R. E. Charlton, Jr., Brian J. Chubb, Laurens D. Dawes, Jr., Dennis E. Enright, James Harris, A. B. Hersey, Thomas Issekutz, Lawrence Pelavin, Michael Samet, Maurice E. Scheetz, Allan L. Sluizer, Q. W. Taylor, Ben Tovrog and one reader whose signature is illegible. I give only Samet's solution, which has a pleasant rhombus formation at the end of the sixth move (the positions are numbered from left to right, starting with 1 at the top): (1) 11–4, (2) 2–7, (3) 13–4, (4) 7–2, (5) 15–13, (6) 12–14, (7) 10–8, (8) 3–10, (9) 1–4, 4–13, 13–15, 15–6, 6–4.

A number of readers also tackled the 21-triangle. The best solution received so far is the following nine-mover from Edouard Marmier: (1) 1–4, (2) 7–2, (3) 16–7, (4) 6–1, 1–4, 4–11, (5) 13–6, 6–4, 4–13, (6) 18–16, 16–7, 7–18, 18–9, (7) 15–6, 6–13, (8) 20–18, 18–9, 9–20, (9) 21–19.

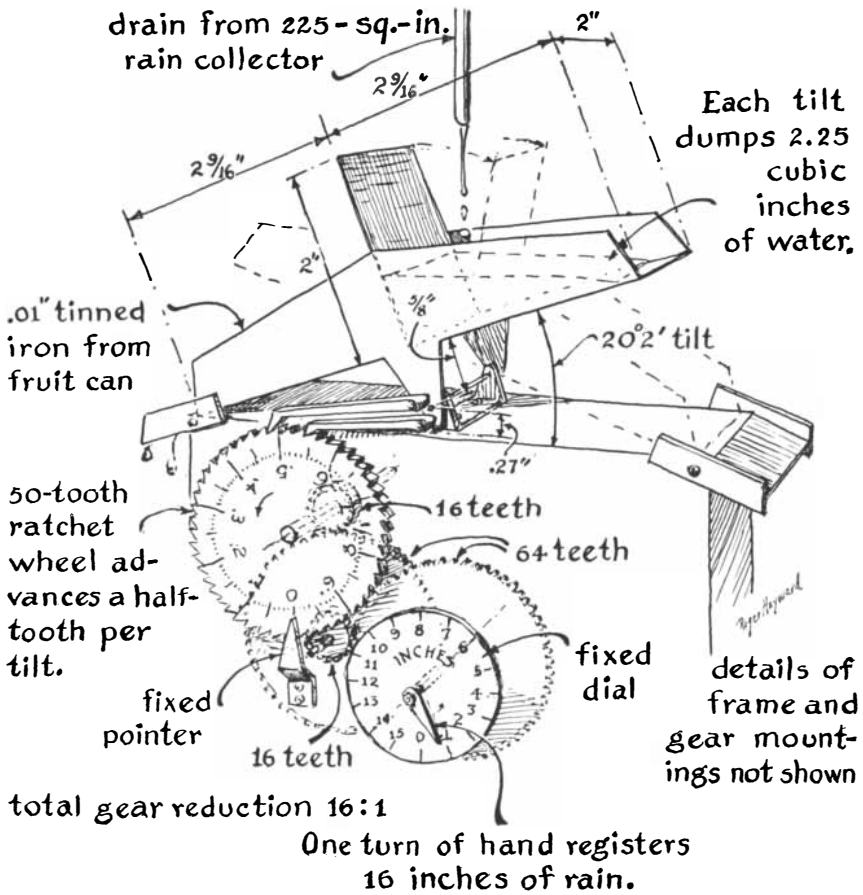
# THE AMATEUR SCIENTIST

*A rain gauge, a fluid flip-flop, a sundial and a way of seeing crystals as they grow*

Conducted by C. L. Stong

Periodically this department presents a collection of enterprises suitable for diversion on a rainy weekend. This month is such an occasion. The projects described are all simple but not necessarily trivial. They require materials that are likely to be found around the house. Each project represents the improvisation of an amateur who was guided largely by the contents of his own scrap pile. Neither the arrangement nor the dimensions of the apparatus are critical. Alter them as you wish. If a project specifies a material you do not have, try something else. All the devices invite further development.

The first device is a rain gauge that automatically records the depth of fall and also empties itself. The idea is submitted by Roger Hayward, whose drawings are a regular feature of this department. The gauge is much more than a measuring instrument; it also illustrates by analogy the functioning of an electronic multivibrator. Such devices are found in television sets, space vehicles and digital computers.




*Details of the automatic rain gauge*

The multivibrator of Hayward's gauge is a fluid oscillator—a miniature seesaw powered by water [*see illustration on this page*]. Essentially the gauge is an open-end trough divided by a thin crosswise partition in the middle. The trough pivots on a pair of supporting legs under the partition.

The water flows into the structure as a narrow stream from a position directly above the middle of the partition when the trough is horizontal. The trough never comes to rest in the horizontal position, however, because it is top-heavy and hence bi-stable. When the apparatus is at rest, one end of the trough is always down and the other up. Accordingly the stream plays against the side of the partition that faces the upper end of the trough.

As this end fills, the accumulating weight ultimately flips the seesaw, discharging the water through the open end of the trough. The stream now plays against the other side of the partition and so initiates the second half of the cycle. Electronic multivibrators, which are sometimes called free-running "flip-flops," operate in the same manner. Two capacitors, counterparts of the divided trough, alternately charge and discharge through a circuit arrangement, which includes transistors or vacuum tubes and constitutes the remainder of the seesaw.

The fluid oscillator can be constructed so that each flip of the trough discharges a predetermined volume of water. When the volume is known, the depth to which a container of known diameter would be filled is easy to calculate. The container that catches rain in Hayward's gauge is a sheet-metal box 15 inches square constructed with a sloping bottom and a drain in one corner [*see top illustration on opposite page*]. A vessel of this size holds 225 cubic inches of water per inch of depth. The trough of Hayward's fluid oscillator is designed to dump 2.25 cubic inches of water per flip. One hundred flips are therefore equivalent to one inch of rain.

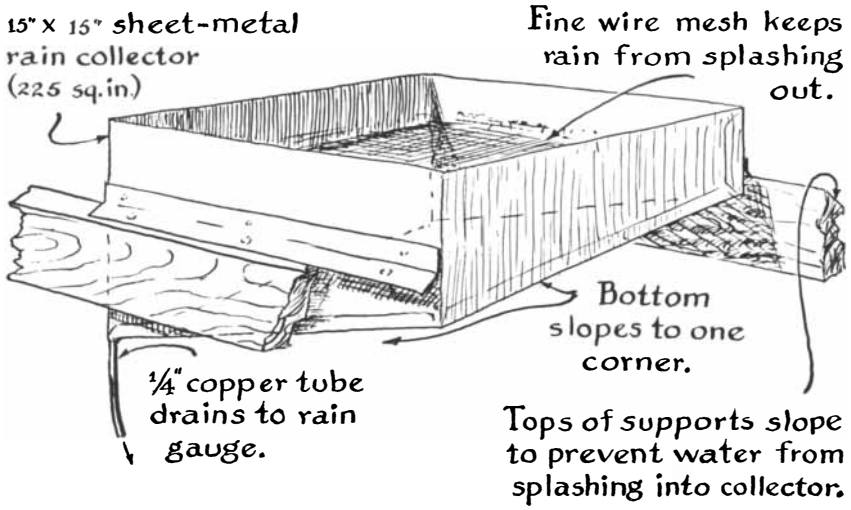
In order to record and display the depth of rainfall Hayward constructed a ratchet motor actuated by a pair of pawls linked to one of the pivot arms of the seesaw. The ratchet wheel advances one tooth per flip-flop and makes one full revolution per inch of rain. A dial on the face of the ratchet wheel is calibrated to indicate .1 inch of rain per division and .01 inch per subdivision. A train of reduction gears that mesh with the ratchet wheel drives the pointer of a second dial for indicating total rainfall to a depth of 16 inches.

Experimenters who do not have the gears can substitute an electrically operated readout device. A set of relay contacts could be fastened to the fluid oscillator for closing a circuit each time the device flips. Electric pulses so generated would actuate an electromechanical counter of the ratchet type. Such counters are available inexpensively on the surplus market. The counter could be installed indoors.

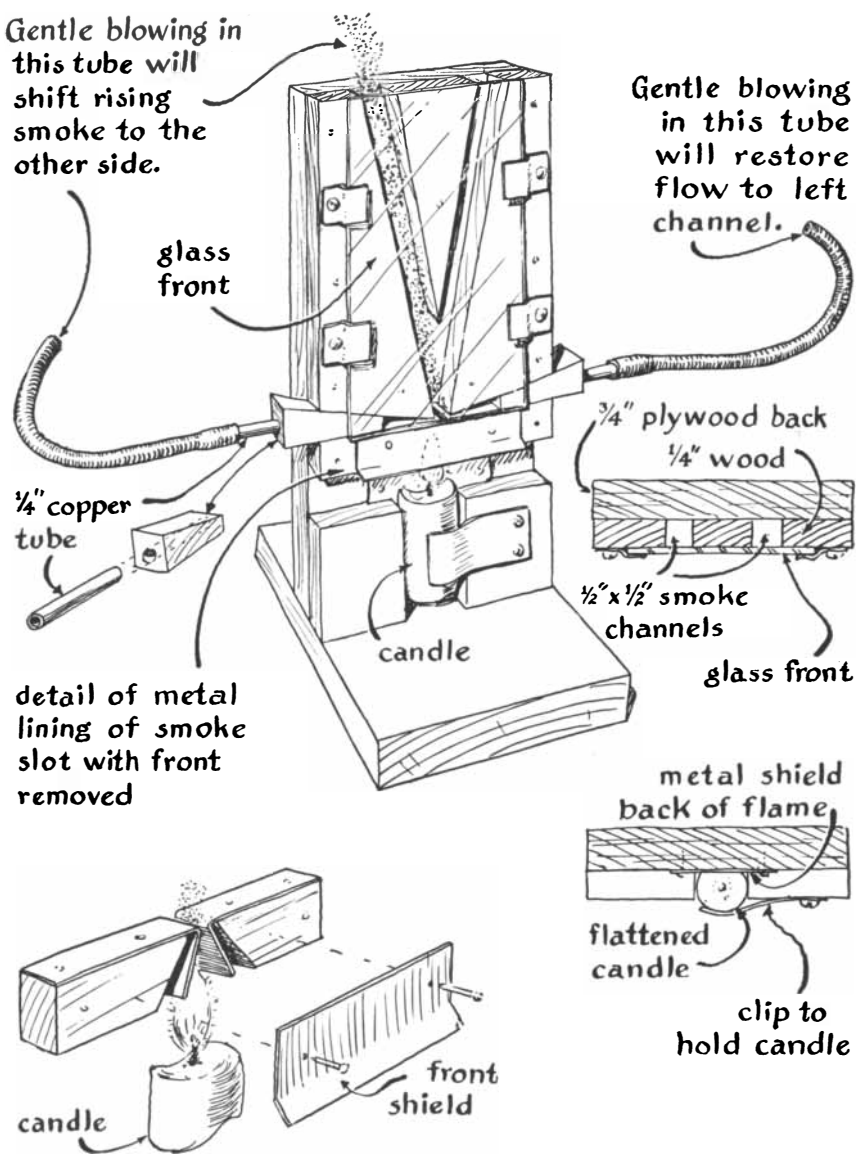
The accuracy of the gauge will be no better than the workmanship that goes into its construction. On the other hand, it is easy to adjust the device after it is assembled. Make the seesaw so that it will flip about 5 percent faster than the desired rate. Then attach an adjustable weight to the top of the partition. As the weight is made heavier increasing amounts of water will be required to flip the mechanism. Find the proper amount of weight by experiment. Insert a piece of screening in the vessel that catches the rain; the screen prevents drops from splashing out of the vessel before they are measured.

James Sharpsteen of Glendora, Calif., submits another version of the fluid flip-flop, this one operated by hot air. It consists of a pair of smoke channels in the form of a V, which is open at the bottom for receiving smoke from a lighted candle below, and two ports that open into the channels on opposite sides at the apex of the V [*see bottom illustration at right*]. Puffs of air can be blown through the side ports by mouth by means of short lengths of flexible tubing. The smoke channels are made of plywood and are closed at the front of the apparatus by a sheet of glass.

When the candle is lighted, smoke immediately enters just one of the output channels. If a gentle puff of air is now sent through the port on that side, the smoke will switch to the other channel and stay there. Hence the device is bi-stable. A puff through the other port will switch the smoke back to the




*A catch basin for the rain gauge*




*Arrangement and parts of the fluid flip-flop*

first port again. The switching action is surprisingly sensitive. It will occur even if the experimenter puffs gently when he is holding the blowing tube several inches from his mouth.

"This quite simple apparatus," writes Sharpsteen, "is an example of an important class of control devices. I have in mind particularly those devices used for amplifying signals, performing computations and making logical decisions [see "Fluid Control Devices," by Stanley W. Angrist; SCIENTIFIC AMERICAN, December, 1964]. I constructed it to help satisfy my own curiosity about such devices."

Having set up the apparatus and switched the smoke back and forth a few times, eliminate the left-hand control port (the wedge is removable) and note that the flow now attaches itself automatically to the wall on the right side, except when a "signal," in the form of a puff, is applied to the remaining control tube. The device is now an inverting amplifier or, in the terminology of computer specialists, a "not" element, because an output flow occurs in the right channel only when there is *not* an input signal.

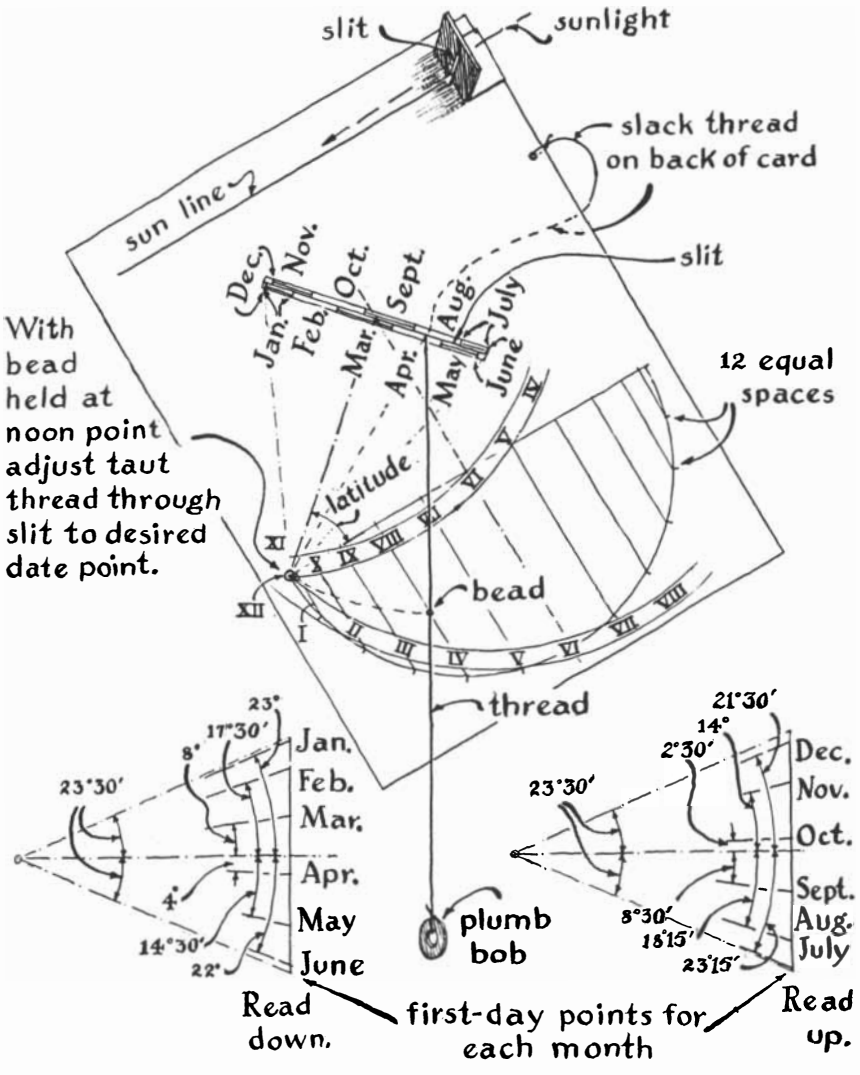
The mono-stable characteristic of the not element is due to the difference in the amount of resistance presented to the flow of air by the openings at the apex of the V. The difference is not large; therefore the action is not always reliable. Adding to the length of the control tube helps, but the best solution is to cut away the wall on the left side.

Now imagine that there are two or more tubes on the right side. Suppose there are three: *A*, *B* and *C*. A continuous stream of air in any one would switch the flow to the left side. That side would then perform as an "or" function, meaning that it would respond to a signal in one *or* another of the available channels. In this case an output would be produced whether the signal entered tube *A* or *B* or *C*. Operating the fluid flip-flop to discover various methods of generating logical functions can be instructive as well as fun.

The device is also instructive from the viewpoint of fluid dynamics. The reason is that the flow is clearly visible, both in the smoke itself and in the patterns of soot that are deposited on the glass. Records of the soot patterns can be made by removing the glass carefully and using it as a photographic negative for making contact prints.

"In comparing the performance of the apparatus with fluid amplifiers that operate on compressed air," Sharpsteen writes, "one must realize that the candle generates only feeble energy in terms of the resulting convection current in the air and that the channels are extremely large with respect to those in conventional fluid amplifiers. The action is therefore somewhat sluggish. Moreover, because the motive power consists of convection currents, the jet can become biased to one side if that side grows significantly warmer than the other. These limitations are balanced somewhat by the fact that laminar flow and leisurely switching speed enable the experimenter to see what is happening. This is an advantage one does not have in the case of conventional fluid amplifiers."

As for the details of construction, half-inch plywood can be used if the nozzle area immediately above the candle flame is protected by sheet metal, such as aluminum. The dimensions specified in the drawing are fairly important but need not be followed exactly. Making certain parts adjustable, such as the smoke-splitter that divides the channels of the V, might be an interesting variation on the design.




*A portable sundial made of cardboard*

While Sharpsteen was having fun in the forefront of modern technology, Frank Cousins of Sussex, England, turned to the 17th century for diversion and came up with a portable sundial invented in 1630 by a Jesuit priest named François de Saint-Rigaud. The sundial can be duplicated in a short time by anyone able to manipulate a compass and straightedge.

Cousins' version of the dial is made of cardboard, a bit of thread, a bead and a small weight [*see illustration at left*]. The device is held by hand at an angle such that a beam of sunlight falls on a "sun line" drawn on

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# FRICTION MATERIALS TESTING

## Ford Motor Company research leads to the application of instrumental friction measurement with Pyrolytic Gas Chromatography

Lengthy vehicle test runs requiring several days are normally needed to test brake lining materials, but new testing procedures developed at the Ford Motor Company Research Laboratories collect pertinent data in 60 to 90 minutes.

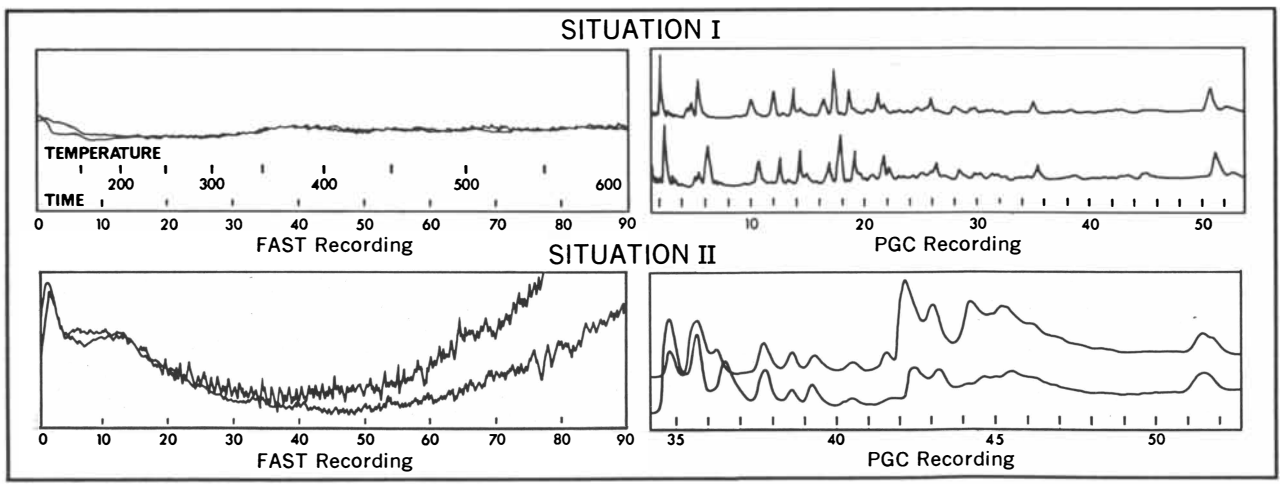
FAST (Friction Assessment Screening Test) was developed to achieve sufficient sensitivity to detect any variations in lining characteristics which might cause erratic or noisy braking. This new technique characterizes a friction material by its wear rate and friction variation with temperature. Performed with constant friction drag and constant sliding velocity, the temperature history and work performed is the same for each sample, assuring accurate comparisons of materials. In addition to the speed with which data can be collected, FAST offers the advantages of providing consistent reproductible results from consistent friction materials.

Once the variations in the friction characteristics of a material are determined, Pyrolytic Gas Chromatography (PGC), is applied to find causes of these variations by analyzing the organic constituents of the material. When a small sample of lining material is pyrolyzed in the PGC instrument, the decomposition products are moved by an inert carrier gas through a packed column, which separates them. As the separated products leave the column, they are detected and recorded as peaks on a strip chart.

The graphs below illustrate the testing procedure. In Situation I, FAST indicates consistent friction level for two samples of a given brake lining material. The pyrolytic gas chromatograms at the right demonstrate the reliability of FAST, showing the organic composition of the two samples to be the same. In Situation II, FAST indicates poor wear-friction comparability between two samples of a different material, and the distinguishing portions of the pyrolytic gas chromatograms show there are variations in the organic composition of the two samples.

The new FAST and PGC techniques permit accurate materials testing and precise component evaluation not possible before. This has led to a more consistent achievement of the quality control standards required for maximum braking performance.

Research of this type contributes to Ford Motor Company's continuing effort to produce safer and more dependable automobiles.




**PROBING DEEPER TO SERVE BETTER**

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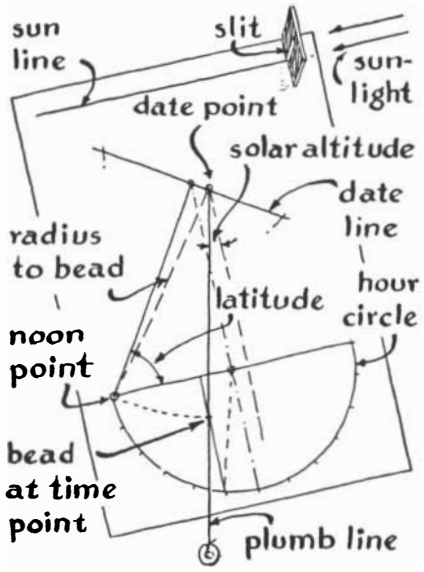
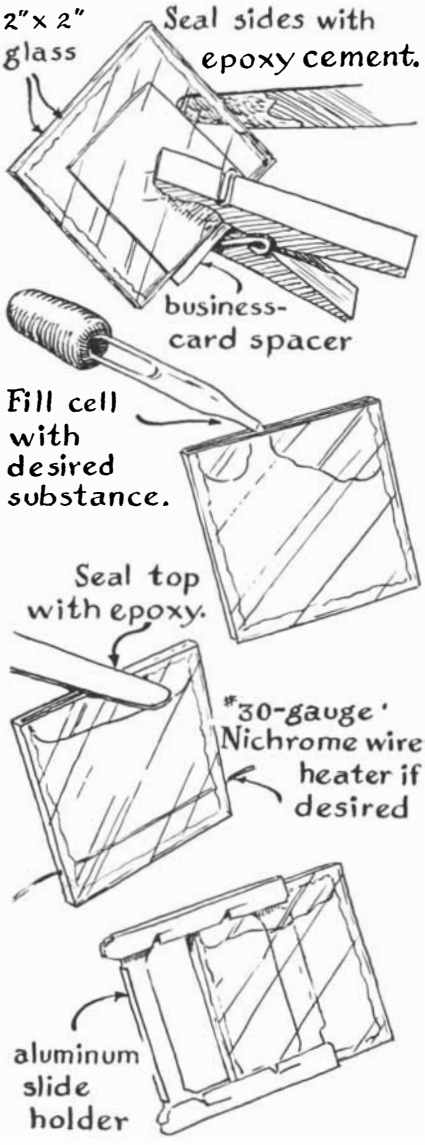



*Geometry of the sundial*




*A cell for growing crystals*

the card. The hour of the day is then indicated on the dial by the position of the bead. The position at which the plumb line is attached to the card must be shifted during the year to compensate for the changing angle of the sun. The proper point of attachment is designated by a scale calibrated in months.

To duplicate the dial cut a rectangle about four inches wide and six inches long from a sheet of durable cardboard. With a pencil and straightedge lightly draw the sun line parallel to and about a quarter of an inch from one end of the card [*see top illustration at left*]. A second parallel line is drawn about two inches from the opposite end. The left end of this lower line is marked "Noon point." Through the middle of these parallel lines draw still another line at right angles to divide the card into equal parts. (Only a segment of this line is inked when you complete the sundial.)

With the intersection of the lower line and the dividing line as a center, draw a semicircle of any convenient radius below the lower line. Divide the arc into 12 equal parts. From the noon point draw a line that inclines upward to the right at an angle equal to the latitude of the geographical location at which the dial will be used. Call this the "latitude line." It will intersect the perpendicular that divides the card. At the point of intersection draw a line at right angles to the latitude line, as though crossing a *T*. This is the "date line." It will be divided into intervals corresponding to months and will be used for locating the position of the plumb line.

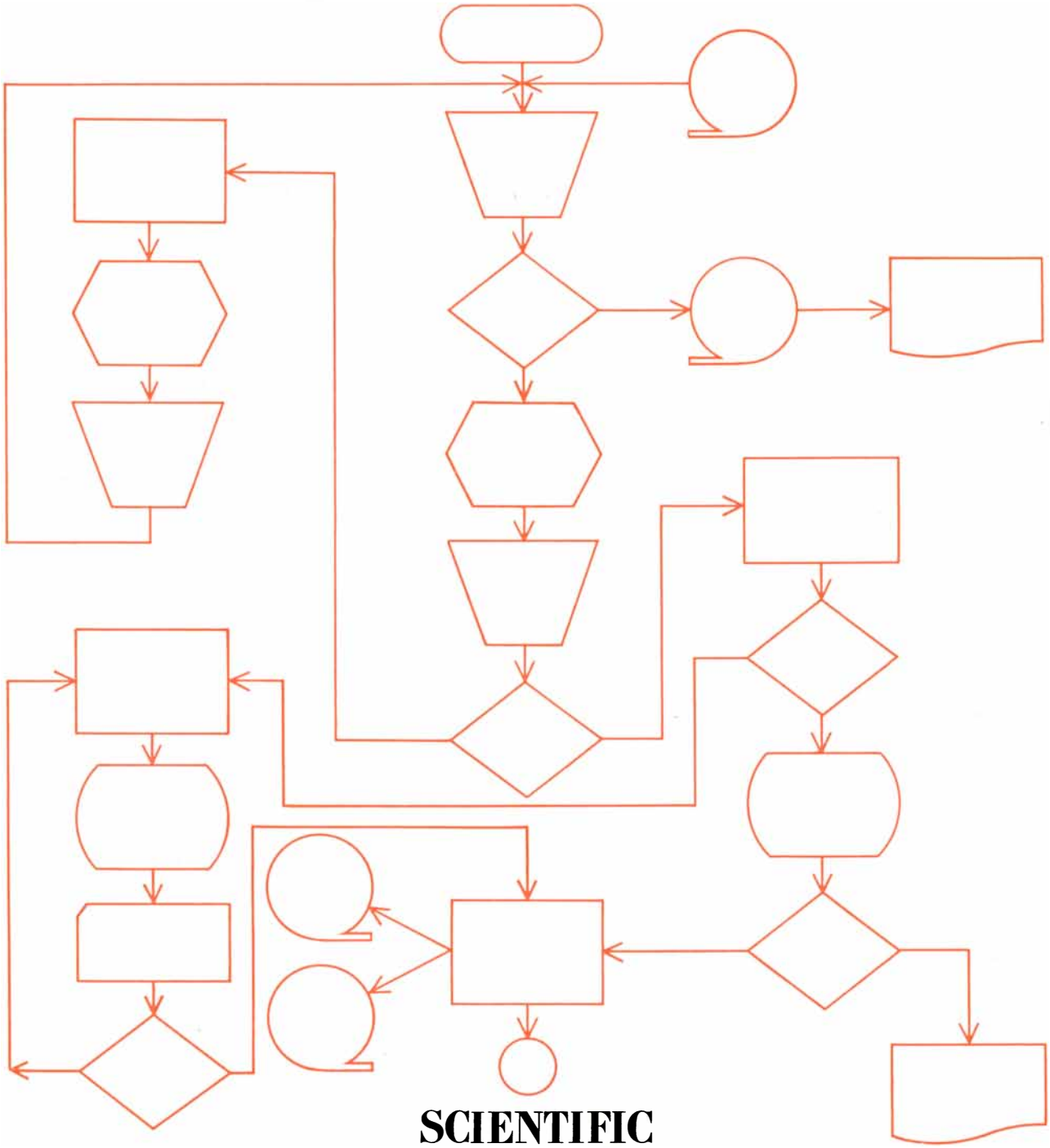
Using a protractor, extend lines from the noon point that make an angle of 23 degrees 30 minutes with the latitude line. These lines will intersect the date line both above and below the latitude line. The lower edge of the date line must now be divided into six monthly intervals to reflect the changes in the sun's declination between solstices. Proceed from left to right. Using the protractor and straightedge, determine the point at which a line would intersect the date line if it were drawn at an angle of 23 degrees between the noon point and the latitude line. It is not necessary to draw the line. Just mark the point of intersection below the date line. Now determine the point of intersection if the line were to make an angle of 17 degrees 30 minutes. Mark the point of intersection. The space between these points is designated January. Similarly, determine the point of intersection of a line drawn at 8 degrees. Mark the point on the date line and label the interval February. The line for March 31 lies on the lower side of the latitude line at 4 degrees, April 30 at 14 degrees 30 minutes, May 31 at 22 degrees and June 30 at 23 degrees 15 minutes.

Proceeding from right to left, lay off the remaining six months on the upper side of the date line. July 1 appears at the lower right end of the date line; July 31, to the left of this point at 18 degrees 15 minutes; August 31, at 8 degrees 30 minutes; September 30, at 2 degrees 30 minutes, to the left of the latitude line; October 31, also left of the latitude line, at 14 degrees; November 30, at 21 degrees 30 minutes, and December 31, at 23 degrees.

With the upper end of the date line as a center and with a radius equal to the distance between this point and the noon point, draw an arc intersecting the line that extends to the right of the noon point. With the same radius draw a similar arc, using the lower end of the date line as a center. These are the hour arcs. Finally, rule a set of parallel lines through the 12 intervals of the first arc you made. These lines are drawn parallel to the line that divides the card in half. Ink in the pencil lines and label the dial as shown in the illustration on page 130.

The plumb line consists of the thread and weight plus a small bead that makes a snug but sliding fit with the thread. Attach the weight to one end of the thread. String the bead. With a razor blade cut a slit through the date line. Insert the thread through the slit and cement the free end to the back of the card at a point near the bottom at the center. To the end of the sun line, at the right, attach a rectangle of cardboard about the size of a postage stamp by means of a linen hinge. This is the folding sight. Make a vertical slit in the rectangle about a sixteenth of an inch wide. (You may prefer to do this before attaching the sight.)

To read the time first slide the thread in the slit of the date line to the appropriate day of the month. The position will of course be an approximation. Pull the thread snugly over the latitude line and set the sliding bead directly over the noon point. Open the sight, hold the card vertically and turn it so that a shaft of sunlight streams through the slit and falls on most or all of the sun line. Release the plumb bob,



**SCIENTIFIC AMERICAN**

*announces a single-topic issue concerned with the technology of*

# INFORMATION

*to be published in September, 1966*

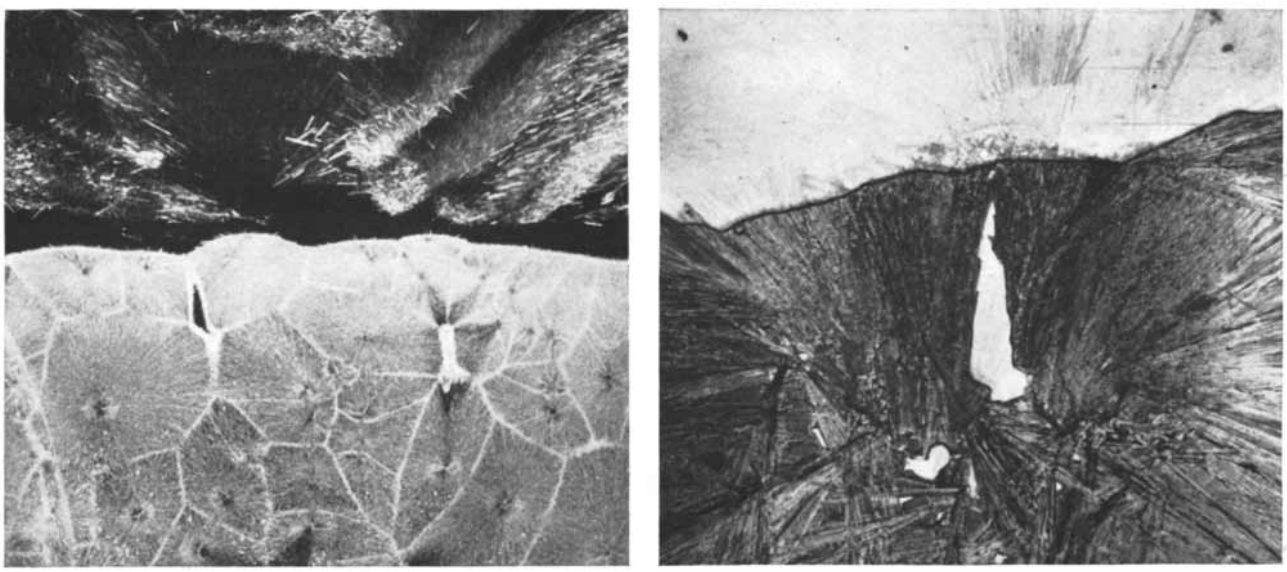
and the position assumed by the bead marks the hour.

"This dial," writes Cousins, "is satisfactory for all locations in the Northern Hemisphere. In the Southern Hemisphere the order of the intervals on the date line must be reversed. The dial is no toy but a small geometric and astronomical instrument of remarkable accuracy. It gives much satisfaction and should be boldly inscribed on the back with the ancient Chinese proverb: 'An inch of time on the sundial's face is worth a yard of jade.' "

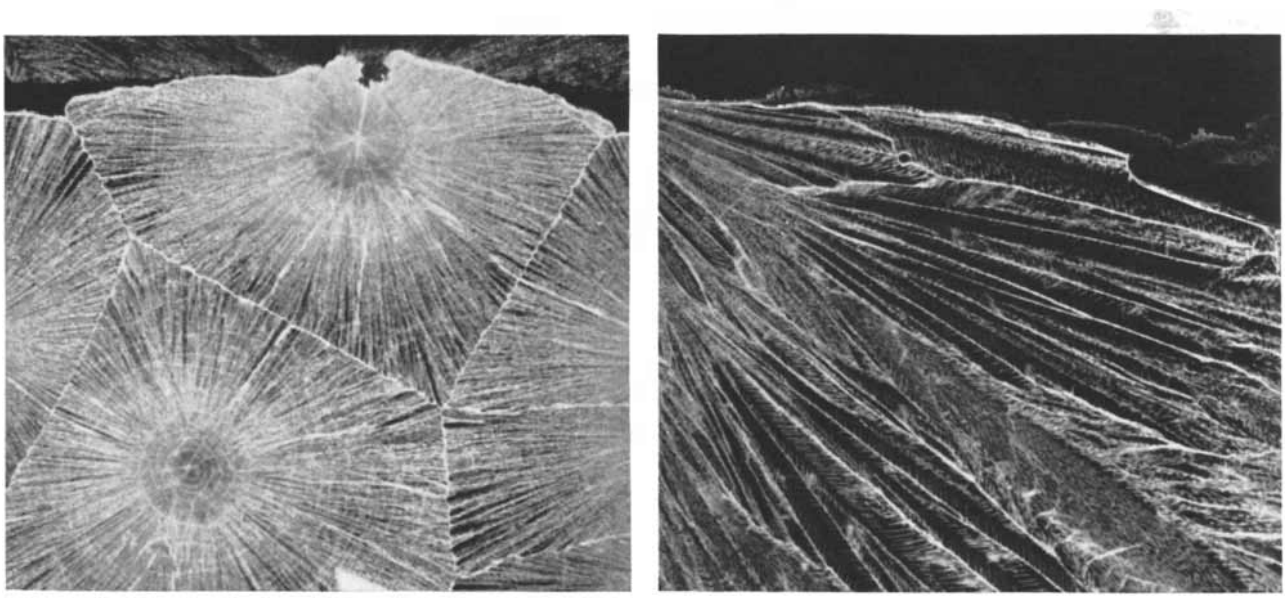
Daniel Gordon, a retired New York pharmacist, admires jewels of a different kind. He makes his own by crystallizing various harmless chemicals; as they grow he watches enlarged images of them on a projection screen. Gordon first makes up a thin rectangular cell from square cover glasses of the kind used for projecting 35-millimeter color slides [*see bottom illustration on page 132*]. A piece of cardboard, such as a business card, is sandwiched between a pair of the glasses and clamped by a clothespin of the spring type. Three edges of the glasses are sealed with a thin layer of epoxy cement. When the cement has hardened, the clamp and card are removed.

A small quantity of a chemical such as thymol, menthol, resorcinol or salol is now placed in a teaspoon and melted by heating the spoon slowly over a gas flame. When the substance melts, approximately one milliliter is taken up by a medicine dropper and put into the cell. The cell should be filled to within about an eighth of an inch of the top. The opening is wiped with a soft cloth to remove the excess chemical and is sealed with epoxy. After the cement has hardened, the completed cell is ready for use. It can be mounted in an aluminum slide holder.

To observe the growth of crystals warm the slide to melt the chemical. Gordon does this by placing the slide flat on a sheet of asbestos paper that he then heats slowly on his kitchen stove. When the chemical has melted, the hot slide is placed in a conventional 35-mm. projector and focused on the screen. Wear a glove when handling the hot



*Crystals of menthol* (left) *and resorcinol* (right); *liquid phase at bottom, vapor phase at top*



*Results of two experiments in growing crystals of salol*

slide. Within a minute or so, depending on the temperature of the slide, the image of one or more minute crystals will appear on the screen. Within seconds these centers will grow explosively into lacy or dendritic patterns that fill most of the screen. Simultaneously crystals of differing patterns will form in the space above the fluid. These grow from the vaporized chemical.

Each chemical crystallizes in a pattern that is characteristic of the substance, but no two patterns of the same chemical are ever identical. The crystals of some substances, such as resorcinol, are optically active: they tend to cause light waves to vibrate in only one plane. When such crystals are examined between two sheets of high-extinction Polaroid—set at right angles to each other so that the pair does not transmit light—crystals appear in all the colors of the rainbow. The color effect can be projected onto the screen by placing a slide of Polaroid behind the glass cell and a second slide in front of the projection lens. The front slide is then rotated until the colors appear.

Gordon is now experimenting with additional chemicals such as acetamide, calcium nitrate, magnesium nitrate, oxalic acid, naphthalene and potassium aluminum sulfate. He invites others to join in the hunt for additional substances that melt and recrystallize at moderate temperatures. According to Gordon, interesting variations can be induced by making wedge-shaped cells. The business card is inserted at only one edge of the glass cell. When the assembly is clamped, the opposite edges of the glass are in contact. The wedge-shaped cavity so formed restricts the crystallization increasingly toward the bottom of the cell and results in a continuous change in the pattern from top to bottom.

In another variation of the technique Gordon binds a short length of fine resistance wire across the bottom of some slides. Iron wire removed from window screening can be used, as can a strand of equally fine Nichrome wire. The ends of the wire are connected in series with a rheostat of about 30 ohms and to the low-voltage terminals of a 12-volt transformer when the slide is in position in the projector. When power is applied, the wire heats and melts the chemical. By adjusting the rheostat the experimenter can control the rate of cooling to alter the size and shape of the resulting crystals and can enjoy a continuously varying display without disturbing the apparatus.

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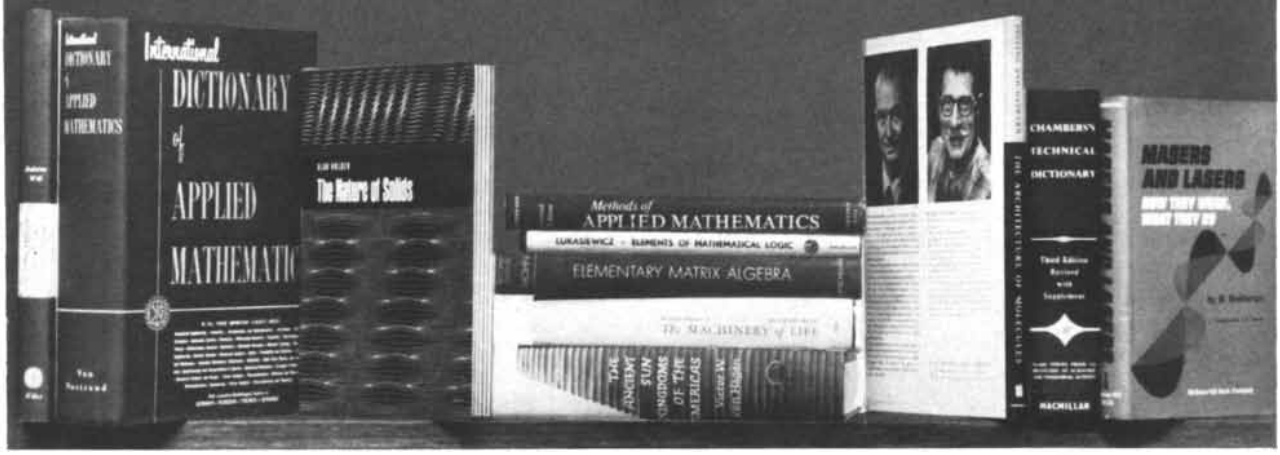


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# BOOKS

## *Ralph Nader and the safety of the American automobile*

by David Hawkins

UNSAFE AT ANY SPEED: THE DESIGNED-IN DANGERS OF THE AMERICAN AUTOMOBILE, by Ralph Nader. Grossman Publishers ($5.95).

Automobile accidents accounted for about 50,000 deaths, or 4 percent of all deaths, in the U.S. last year. They caused 16 percent of the nonfatal injuries and 36 percent of the injuries involving permanent impairment. The average age at death by automobile is 38, in contrast with that in other categories, which is 62. Thus if we count man-years destroyed rather than men, the 4 percent figure goes up to 7 percent.

Such is the ranking of the automobile accident among the causes of death and disablement, yet we neglect to use known means of reducing injury rates, or to study new ones. For such research there are no national fund drives and few research institutes, public or private. Still, in spite of its destructiveness the automobile is of the essence of American life, and the automobile industry is a pillar of the affluent society. It seems proper that we confront ourselves with a new definition of the problems and responsibilities of accidental death on the highways. Affluence brings with it many resources for an attack on the problems, but it does not automatically generate the will to attack them.

Such an attack will not come easily or quickly. Competition among advocates is certainly going to be the order of the day. The President promises support for major traffic-safety legislation, including support for basic research on accidents. The manufacturers and the insurance companies are bestirring themselves. Everyone is in favor of greater safety, but to infer a corresponding political unanimity would be excessively naïve. Deeper issues are involved.

For decades we have followed the policy that greater automobile safety was to be achieved primarily by campaigns of driving legislation, law enforcement, technical education and moral exhortation. This view has had, and for many it still has, the force of an ideological commitment. Nader's book can be described as an analysis and a critique of this ideology. It is an adversary work that points an accusing finger at the automobile manufacturers, charging them with indifference, callousness and arrogance in the face of genuine possibilities of safer automobile design. In his conclusion Nader advocates publicly defined and Federally enforced standards of safety in design and manufacture, supported by continuous research. Because of the adversary character of the book I wish to put it in the somewhat wider context necessary, I think, to any sane resolution of the issues Nader is attempting to define and dramatize.

Certainly I cannot adjudicate all the issues as he defines them. Reactions I have sampled, from the industry and its supporters, range from scorn and outrage to the charge of half-truth or the suggestion that a far more qualified statement would be more effective. In defense of the industry one may offer this much: Detroit is part of America, and its engineers and policy-makers drive cars. Corporations are highly adaptive entities, and we should not be surprised if the car manufacturers' view of safety were essentially that of the general public, one of indifference or unfocused anxiety. If there is blame, Detroit can share it with the rest of us. For the prosecution, however, one can make a charge appropriate for any who hold a public trust: that they should be ahead of all others in their concern for the public welfare. Where safety is involved car manufacture should be judged as a profession, not as a trade. By such a standard, and without regard to Nader's book, the Detroit score is not high. The score surely did not rise with the news that private detectives, employed by General Motors, had harassed Nader by extensive inquiries into his private life, his views and associations. James M. Roche, the president of General Motors, apologized for this act of his company before the Ribicoff subcommittee of the Senate on March 22. This investigation, presumably initiated by Roche's subordinates in the General Motors legal division, suggests the prevalence of attitudes toward external critics that are scarcely those of self-conscious searchers after the truth about automobile safety. I am sure that such attitudes are not shared in the General Motors research division. Could Roche not find a way of letting us hear of the views and activities of *that* division? It would be, I think, a redemptive sequel.

The dominant view of automobile safety—"It's the driver's fault"—has obvious political implications. One implication is that a greater concentration of effort on the design of vehicles and traffic systems from the standpoint of safety will produce only minor results. Another is that the car, and behind the car its manufacturer, should not be regarded as a significant factor in accidents, except perhaps for a special and rare class of them. Accordingly Government-imposed safety standards are sure to be ineffective. Moreover, such standards are morally wrong; they imply responsibility for accidents on the part of innocent manufacturers and exculpate guilty drivers. This, of course, is a classic stance of free enterprise: *Caveat emptor!*

Having such obvious political relevance, this dominant view must be taken very seriously. When we take it so, we discover that it is (1) irrefutable, (2) irreproachable and (3) irrelevant to any question involving the safety design of vehicles. The dominant view is irrefutable because in all but a special class of cases it is proper to say—in retrospect—that a given accident could have been avoided had one or more drivers involved behaved differently and more nearly in accordance with fine prudential maxims such as "Don't drive too fast for the conditions." This view is

irreproachable because in one important sense we are all morally bound to subscribe to it: *given* the state of the cars, the highways and other drivers, we must always accept the responsibility for driving as alertly, intelligently and cautiously as we know how. The view is irrelevant because it implies that a reduction of accidents can be achieved by the improved performance of drivers but in no way implies that improvements in design could not bring about a much greater reduction—as in fact appears to be the case. Let us take at face value the statement that "90 percent of accidents are due to faulty driving." Let us now hypothetically consider the reduction of fatalities to a third of their present level through the radical redesign of vehicles, assuming no change in the skill of drivers or their dedication to safety. It might then remain true that "90 percent of accidents are due to faulty driving." Meanwhile there would be 30,000 fewer Americans killed each year, including some careless drivers.

The 90 percent statement is an interesting one. What does it mean? I suppose it means that police investigators, looking for driver fault defined in some commonsense way, find it 90 percent of the time. It is quite clear, however, that another investigator, looking for machine-design fault, highway-design fault and so on might also find each of these to be present in 90 percent of the cases. "Faults" talked of in this way are not mutually exclusive sufficient conditions for accidents but are mutually consistent necessary conditions. The glib transition from one interpretation to the other marks the whole line of argument as invalid.

But is the dominant view really only an inglorious *non sequitur* serving the negligence of manufacturers and the servility of what Nader calls "the safety establishment"? I feel its roots are deeper than that. We as a people (and others even more so) are not yet equipped to think well about the problem. It may sound odd to say it in this age of aeronautical and astronautical achievements, but the automobile has outstripped us in the intellectual, moral and aesthetic capacities we need for coping with it, and the result is chronic foolishness, bad taste and venality. It is essentially a 19th-century invention and represents a jump in vehicle speeds by only a factor of 10 or so over the speeds available before. A tenfold increase in speed, however, is a hundredfold increase in kinetic energy and peak forces. Our predominantly pre-Newtonian commonsense intuitions do not stand up against so great a change. Thus far we have done little to replace our primitive near-zero-velocity intuitions with properly Newtonian ones.

A part of the machine, considered as an operative system, is the driver, whose cognitive and control processes must operate in this Newtonian milieu. High-velocity operation places demands of a novel kind on the organism, requiring discriminations of size, distance, velocity, direction and acceleration for which we are poorly equipped. It also implies a need for feedback mechanisms that has hardly been explored. I have a fantasy of electronic sense organs at the interface of the tire and the road, for example, coupled to the driver's tactile sense and pain responses. This would surely have a marvelous effect on cornering and braking. The evolution of the car-driver interaction is still quite primitive, and the sense in which the driver is the car's master is correspondingly limited. In this connection let me abstract from Nader's book a quotation from H. E. Humphreys, Jr., of the U.S. Rubber Company, that restates the dominant view in a way metaphysically appealing to pre-Newtonian—even Aristotelian—intuitions: "Being inanimate, no car, truck or bus can by itself cause an accident any more than a street or highway can do so. A driver is needed to put it into motion—after which it becomes an extension of his will."

The confrontation we need is a matter of the most obvious humanity and utility, but it goes deeper. We should find imaginative ways of cultivating our Newtonian intuitions, of refining our discrimination and taste in things automotive. We ought not to require statistics, as defenders of the dominant view are likely to urge, to prove that poorly anchored seats or glare from chromium-plated decorations is dangerous. We ought to dislike such things without need of grisly evidence. We should cultivate the easy awareness of forces, masses, accelerations and our own limitations as high-speed feedback controls. And we should appreciate some subtleties of higher order—some feeling for the phenomenon of gyration, of static and dynamic friction, for the behavior of rubber under stress, for the elastic limits of steel frames or flesh and bone. It implies an improvement of taste to accept the seat belt and reject the knobby instrument panel. After two decades of soft tops called "hardtops" might we not come to see roll bars as rather elegant? It is certainly an improvement of taste to reject the jagged external decor recently so characteristic of our vehicles and see it as a collection of potential meat choppers. As a symbol of the worst I offer those charming hub decorations of flashing knives, presumably inspired by Ben-hur or James Bond.

In his examination of the dominant ideology, Nader has dug extensively into a variety of public and private sources: court records, patent applications, automobile magazines, the publications of standards groups and safety groups, engineering journals, the records of hearings and the transcripts of meetings. It is unfortunate, in this connection, that the book has a "popular" format, without adequate references. A fair number of essential references can be found in the text or inferred, but it is not easy. Some circumstantial accounts in the book are evidently based on private communications. The book goes principally in three directions: toward the record of past performance, to study failures in design or quality control; toward the research frontier, to define potential levels of vehicle safety, and finally, toward the record of the attitudes and policies of the automobile manufacturers, the tire manufacturers, the insurance companies and the many automobile associations and groups concerned in one way or another with safety. Therefore although the book contains a great variety of information about specific design problems and possible solutions, its focus throughout is on the entire system of beliefs and attitudes that penetrate and surround this remarkable industry. It is thus primarily a case study in economic and political sociology. It is not, however, detached and academic in tone. Nader is a lawyer, and his tone is relentless. His case is carefully constructed, and it brings together for the first time an impressive collection of factual information. The line of argument is clear but not lacking in subtlety, as in the interplay of contrasts in the treatment of Detroit's engineer-spokesmen and its "stylists." The relentlessness is qualified by occasional counterexamples. In his treatment of research organizations that are responsible for valuable safety information but that he sees as improperly influenced in their publication policies by company support, Nader manages both praise and blame; he also manages to make clear how little support there is as yet for first-class research. Having described this work as adversary and praised it, I must add that the proceeding will not be complete until we have had some careful and equally analytical replies

that do their best with denials, counter-examples and reinterpretations. In the old days this book would have been called muckraking, but it formulates real issues that ought to be joined.

A good deal of the force of Nader's presentation depends on a case-study technique. His first chapter is devoted to design weaknesses in the Corvair of 1960 to 1963, specifically the combination of its rear engine and rear swing-axle suspension, which under certain circumstances produce a sudden "tuck-under" of the rear wheels and a loss of control. The story is that of a lawsuit brought against General Motors as an aftermath of such an accident, a prototype of many other such suits. The account produces evidence that the dangers involved in this car design are well known to accident investigators, to dealers and independent accessory manufacturers—and to General Motors. There follows a history of the Corvair, to show that both the hazards and the means of avoiding them (finally adopted in 1964 and 1965) were fully known ahead of time.

In the succeeding chapters Nader makes similar use of a variety of materials: brake failures in a 1953 Buick series, a defective suspension arm in a 1965 Ford series, a defective steering-system bracket in 1965 Chryslers; the "PNDLR" automatic gearshift pattern common to the Cadillac, Buick, Oldsmobile, Pontiac, Studebaker and Rambler for many years. This pattern makes possible a dangerous confusion between L (low gear) and R (reverse), as many records of "driver negligence" will show. I myself am fortunate in not being included in the records, having once "shifted down" into reverse at the beginning of a steep hill! The negligence was real, as is the fact that it would not have happened with the now approved "PRNDL" pattern.

Next there is a series of case studies involving "the driver's right to see": optical distortion, poor wiper and defroster design, inadequate mirror design, glare from reflecting surfaces, obstructing corner posts, tinted windshields. At a time when car stylists lean heavily on glamorous lines borrowed from aircraft, it would be pleasant to see cars embody one universal feature of aircraft: the elimination of shiny surfaces in front of the pilot. A good many specific items in the list have been corrected, more or less, presumably to the credit of the manufacturers. Nader makes his case here by a running stream of references and quotations to show that changes have often been

delayed, grudging and (recently) impelled by the appearance of legislated safety standards on Federally purchased cars, by Congressional hearings and the threat of legislative controls.

A most interesting discussion in the book has directly to do with the consequences of high collision-accelerations, in the range of tens of g's. Put in terms of forces, an unrestrained passenger strikes the windshield, the instrument panel or the steering wheel with what Leonardo da Vinci called "a weight in the direction of motion" of several tons. Such forces can be transiently endured (as Colonel John Paul Stapp showed in special deceleration apparatus) when forces are properly distributed over the body area. Energy-absorbing bumpers—not the prevailing sheet-metal décor—can considerably decrease peak forces by lengthening the collision time. Many simple interior-design changes can reduce peak pressures on the body by eliminating projections with which the body can collide. The steering wheel, the most lethal of all these projections, can be designed against being displaced to the rear and impaling the driver, and also to absorb the energy of his forward motion. Seat belts and even more effective restraints are an obvious necessity.

A completely different aspect of the design problem is the reduction of hydrocarbons and carbon monoxide in automobile exhaust gases. Hydrocarbons have been known for 15 years to be major contributors to photochemical smog, and carbon monoxide is highly toxic, possibly contributing to driver failure on crowded highways. In a separate chapter Nader tells the story of the struggles of the Los Angeles Air Pollution Control District, and of legislative bodies, to elicit from Detroit the acknowledgment of the reality of the problem, contributions to research on it or innovative action without the necessity of legislative compulsion.

Nader's final chapters deal with the expressed outlook of Detroit's safety engineers, whom he sees as public relations spokesmen assigned to the task of keeping the public unalarmed about safety problems; with the standardization policies of the Society of Automotive Engineers and the American Standards Association, and with the publicly stated position of the Automobile Manufacturers Association. In contrast to the enforced servility Nader ascribes to safety engineers who work for automobile companies he sets the increasing status of the design stylists, who are chiefly responsible for maintaining a high annual volume of sales.

To round out Nader's picture there is a survey of the system of organizations that he collectively labels "the traffic safety establishment." This consists of numerous national groups, united behind the dominant ideology of driver error. There is a good deal of space devoted to the President's Committee on Traffic Safety, largely financed by Federal funds and devoted, according to Nader, to the maintenance of "safe" Federal policies approved by its industry-sponsored policy makers. Finally, he describes the work of the National Safety Council, which he sees as a hotbed of indifference to any matters of safety other than its own extensive driver-safety program. Perhaps this program, coordinating the efforts of regional and local organizations, has had some effect over the years. Our record is better, as far as I can ascertain, than that of other countries. The main reason, of course, is that we have been at the business longer than other countries. Conscious safety propaganda, and thus the National Safety Council, may still count for something. The council is in fact a relatively small organization, best known to the public for its holiday-accident forecasts. These urge drivers to ever greater caution at just those times that are, as I calculate, statistically the safest: on national holidays the accident rate goes up by considerably less than the volume of traffic, thus decreasing in terms of vehicle miles.

In his last chapter Nader reviews the beginnings of Federal action on the issues of safety, starting with the Roberts subcommittee hearings begun in 1956 and continuing to the Ribicoff hearings of last year. He devotes considerable attention to the General Services Administration standards on Government cars, brought into existence as a result of work by the Roberts subcommittee. What Nader advocates is publicly defined and Federally enforced manufacturing safety standards, maintained and extended by continued short- and long-range research. In order to be successful such a program must have a "supportive constituency" of independent engineers, physicians, lawyers and psychologists, all well informed and devoted to the interests of safety.

Reluctance on the part of Detroit to acknowledge the need for or the possibility of far higher standards than those that now prevail can only intensify the persuasiveness of Nader's position. Is such reluctance inevitable? Could not the manufacturers decide that the potentialities of automobile safety are a new source of sales-stimulating annual innovation? I will not be outdone in skepticism that this decision is likely, but in fact there is no historical necessity in the manufacturers' traditional view. That view includes the belief that a strong emphasis on safety design brings no competitive advantage. In actuality the belief has never been tested. Cannot the community of automobile manufacturers find ways to commit its members to such an emphasis? Legislation can force some such commitment, but it is better to lead than to be dragged.

## Short Reviews

LIQUOR: THE SERVANT OF MAN, by Morris E. Chafetz. Little, Brown and Company ($4.95). "Drinking," wrote Thomas Fuller, "hath drowned more men than Neptune." Said Bernard de Mandeville: "I believe more people break their brains by drinking than study: for though the latter may be troublesome enough, yet a book is not so hard as a bottle." Othello's Cassio, regretting a drunken quarrel, laments: "O God! that men should put an enemy in their mouths to steal away their brains." The defense is better armed. "Eat, drink and be merry," we are instructed by St. Luke. "No longer drink only water," Timothy was advised, "but use a little wine for the sake of your stomach and your frequent ailments." Socrates held that as plants need water to grow straight and tall and bear abundant fruit, so it is with us and wine. The 17th-century Henry Aldrich gave a compact argument:

*If all be true that I do think,*
*There are five reasons we should drink;*
*Good wine—a friend—or being dry—*
*Or lest we should be by and by—*
*Or any other reason why.*

No less cogent is Robert Burns's plea for the Scotch beverage:

*When neeburs angry at a plea*
*And just as wud as wud can be,*
*How easy can the barley-bree*
*Cement the quarrel*
*It's aye the cheapest lawyer's fee*
*To taste the barrel.*

Even before rising to General Grant's support ("If I knew his brand, I'd send cases of it to my other generals"), Lincoln said in a speech at Springfield: "If we take habitual drunkards as a class, their heads and their hearts will

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bear an advantageous comparison with those of any other class." Winston Churchill, who devoted a lifetime of assiduous research to the subject, observed: "I have taken more out of alcohol than alcohol has taken out of me."

In this book a Harvard psychiatrist, who is also director of the Alcohol Clinic at the Massachusetts General Hospital, appears as *amicus liquoris* to add his expert opinion to the brief. Liquor, in Chafetz' view, is, and has been for thousands of years, a boon to mankind. It makes life less nasty. It promotes health. It improves the company. It eases tensions. It lightens the burden of moral obligations that are beyond a mortal's capacity to bear. It is man's portable, uncomplaining, ever faithful servant. When taken in moderation, of course—an agreeably vague word that each must interpret for himself. In short, although alcoholism is a major public health problem, liquor is not.

Chafetz is an enthusiast. He likes to drink. He enjoys good health. He is a persuasive advocate, if persuasion is needed; he is in fact sometimes carried away by his cause, as when he tries to prove that liquor has been a major civilizing force in history. The great merit of his essay, apart from its cheerfulness, is that it commandingly dispels vulgar errors, foolish fears, confusions and stereotypes. Here is a sample. Alcohol, often spoken of as a stimulant, is in actuality a depressant. This accounts for one of its benefits: by slightly dulling the brain it rounds off the jagged corners of experience. Popular myths to the contrary, nothing can be done to hasten the departure of alcohol from the body once it has been imbibed. The liver destroys 100-proof alcohol at a rate of about one ounce per hour, and neither exercise nor sleep nor a turkish bath will accelerate the process. Alcohol is so rapidly absorbed that it begins to exert its effects within a few seconds of being swallowed. The chief deterrent to this absorption is either the dilution of the potion itself or the drinking of water immediately after swallowing the liquor.

"There is no sound evidence whatsoever that alcohol causes permanent direct damage to the body." A direct causal effect of alcohol on kidney disease has not been shown; alcohol cannot be incriminated, on the basis of available information, in cirrhosis of the liver; it does not, as so often has been charged in one way or another, eat away, turn to stone, vulcanize or otherwise ferociously attack the main organs and functions of the body. It may be admitted, however, that drinking will scarcely improve kidney disease, mend an ulcer, cure hepatitis or alleviate other organic disorders.

Alcohol does not of itself make you fat; it is oxidized so quickly and efficiently that it cannot be stored. Nevertheless, drinking can add to fatty tissue because the body, having the energy from the alcohol available, does not metabolize solid food taken along with it; the result is that the food "gets tucked away as future energy in the form of weight." Alcohol aids digestion by acting as a relaxant. It does not dehydrate the body. The piercing thirst that is one of the outstanding features of a hangover comes not from any decrease in the body's water content but from the shift of body fluid from the cells to their immediate environment.

Among other topics that Chafetz discusses are liquor and sex, teen-age drinking (teen-agers may have troubles that lead them to drink, but there is no known correlation between drinking and teen-age troubles), drinking and driving (not recommended), liquor habits around the world. The author is to be congratulated. He has done almost as well by the tippler as Izaak Walton did by the fisherman.

JANE'S ALL THE WORLD'S AIRCRAFT: 1965–1966, compiled and edited by John W. R. Taylor. McGraw-Hill Book Company ($42.50). *Jane's Aircraft* is 56 years old. Like the aircraft industry, it gets bigger and more specialized every year. *Jane's* is now, as it always has been, an absorbing book to browse in. It is even more interesting than a mail-order catalogue—and most of its contents are as useless to the average reader.

Among the new entries are the subsonic C-5A program, which is intended to produce for the U.S. Air Force a four-turbofan heavy logistics transport weighing between 250 and 375 tons. General Electric has been awarded a contract to develop the power plant for such an aircraft; Boeing, Douglas and Lockheed "still await the result of the airframe design competition for which they have tendered projects." There is considerable uncertainty as to the advisability of packing 500 to 750 passengers into a huge air bus of this kind. Handling the passengers at the terminals is likely to produce a king-sized headache; one has visions of a need for a moving platform in the plane itself to get the passengers into their seats in

less time than the journey on which they are embarking will consume. The Russians, it is said, have decided that the advantages outweigh the problems. The arrival of their enormous AN-22 over Le Bourget during the Paris air show last June was followed by an official statement that an even larger 720-passenger version is being built for nonstop air bus service across the U.S.S.R.

At the other end of the scale craft are being designed for amateurs. Their needs are being catered to by the homebuilt movement, "which is mushrooming at an incredible rate in many parts of the world." Included in this category is a single-seat sporting biplane named the Old Hen Crow, designed by Arthur G. Whitacre of Fort Wayne, Ind., which with an 85-horsepower engine does 130 miles per hour, has a landing speed of 55 m.p.h., a service ceiling of 8,000 feet, an empty weight of 592 pounds, costs less than $2,000 to build and looks exactly like an old hen crow. Also listed are E. L. Turner's Ophelia Bumps, another do-it-yourself sporting aircraft that can do 170 m.p.h.; George W. Meyer's fully "aerobatic" biplane known as the Little Toot, of which eight examples are now flying in the U.S., with at least 75 more under construction; Bensen Aircraft's B-9 Little Zipster, which is a pure helicopter (not homemade) and about as safe-looking as a manually operated eggbeater perched on a rope across Niagara Falls; Vernon W. Payne's Sunday Knight Twister, a sporting biplane that has a speed of 178 m.p.h., looks like a tie clasp with wings and is presumably intended to give pleasure to the Sunday flier who wants to fly in a tie clasp. It is clear that the age of wonderful men in their flying machines is far from over.

HISTORY OF EUROPEAN THOUGHT IN THE NINETEENTH CENTURY, by John Theodore Merz. Dover Publications, Inc. ($11). A four-volume reprint in soft covers of one of the great surveys of human thought, first published in Britain between 1904 and 1912. The first two of Merz's volumes cover 19th-century scientific thinking in Britain, France and Germany having to do with mathematics and the natural sciences from astronomy and physics to genetics and morphology; the second two are concerned with philosophy. Merz was an admirable writer—beautifully clear, always interesting, with an almost unbelievable grasp of the many departments of the vast subject with which he was dealing and a sureness in dis-

cerning essentials and fashioning his descriptions. His book, which has given comfort and intellectual stimulation to two generations of readers, has been out of print for many years. It is a literary event to have it now made available in an inexpensive edition. Not for the first time Dover Publications deserves to be congratulated.

CHARLES DARWIN AND HIS WORLD, by Julian Huxley and H. B. D. Kettlewell. The Viking Press ($6.50). It seems a little surprising at this point to have another biography of Darwin, there having been a great outpouring of writings about him and his work to commemorate the centenary of the publication of *The Origin of Species*, including an excellent biography by Sir Gavin de Beer. The justification is presumably the placing of greater emphasis on Darwin's discoveries than on his life, and also the abundant illustrations, many of contemporary vintage, that have been skillfully selected and that afford much pleasure. The book is not always as clear as it might be in explaining the complexities of the theory of evolution to the ordinary reader. Huxley and Kettlewell are so deeply versed in this subject that they are inclined to forget how easily the nonexpert can get lost in the thicket of subtleties. For the illustrations alone, however, this is a desirable volume even for those who are unable to follow some of its more complex sequences.

PROJECTIVE GEOMETRY, by Oswald Veblen and John Wesley Young. Blaisdell Publishing Company ($5.25). A paperback edition of a famous mathematical text by two leading American mathematicians, both deceased, first published some 55 years ago. Every advanced student of this subject, including Norbert Wiener (who refers to the book admiringly, in his autobiography *Ex-Prodigy*, as forming his introduction to the subject), has used Veblen and Young, and it continues to hold a high place, not merely for historical reasons, in the literature of mathematics.

MEMORY: A CONTRIBUTION TO EXPERIMENTAL PSYCHOLOGY, by Hermann Ebbinghaus. Dover Publications, Inc. ($1.50). A reprint of the translation of the psychological classic of 1885 that extended the then new experimental psychology beyond the study of sensation and perception to the measurement of learning and memory. An introduction by Ernest R. Hilgard shows clearly how Ebbinghaus brought psychology forward, how far he advanced and corrected the conventions of his day and how modern he still remains in several of his innovations.

THE THEORY OF ATOMIC COLLISION, by Nevill F. Mott and Sir Harrie Massey. Oxford University Press ($19.20). The third edition, completely revised and substantially expanded, of a monograph by two eminent British investigators. Since the second edition, published in 1949, much research has been devoted to the subject, the results of which are incorporated here.

## Notes

CONTEXT AND MEANING IN CULTURAL ANTHROPOLOGY, edited by Melford E. Spiro. The Free Press ($9.95). This book, written in honor of A. Irving Hallowell, a prominent student of modern anthropology, deals with many different aspects of cultural anthropology, its contributors representing the biological as well as the social sciences.

FUNCTION AND STRUCTURE IN MICROORGANISMS. Cambridge University Press ($13.50). A record of the 15th symposium of the Society for General Microbiology, held in London in 1965, concerned primarily with the question of how the intricate structure of microorganisms is correlated with the functions they perform.

ADVANCES IN EXPERIMENTAL SOCIAL PSYCHOLOGY: VOLUME I, edited by Leonard Berkowitz. Academic Press Inc. ($9). This volume, which initiates a new series intended as a repository of information derived from observations and research in social psychology, contains pieces on such topics as cultural influences on cognitive processes, coalition formation, inducing resistance to persuasion, sociability and social organization in monkeys and apes.

DIFFERENTIAL AND COMBINATORIAL TOPOLOGY, edited by Stewart S. Cairns. Princeton University Press ($8.50). Fourteen mathematicians contribute technical papers on topology to a symposium in honor of a longtime researcher in the field: Marston Morse, professor emeritus at the Institute for Advanced Study.

STELLAR STRUCTURE, edited by Lawrence H. Aller and Dean B. McLaughlin. The University of Chicago Press ($17.50). The eighth volume of this nine-volume compendium of astronomy

and astrophysics considers problems of the internal structure of stars, their evolution and the sources of stellar energy.

STEELMAKING: THE CHIPMAN CONFERENCE, edited by John F. Elliott and T. R. Meadowcroft. The M.I.T. Press ($20). This volume of proceedings of a conference held to commemorate the career of the metallurgist John Chipman contains papers on steelmaking in all its phases.

ANIMAL INTELLIGENCE, by Edward L. Thorndike. Hafner Publishing Company ($4.75). A reprint of a study of animal intellect and behavior first published by a pioneer in this field more than half a century ago.

ROMAN LIFE AND MANNERS UNDER THE EARLY EMPIRE, by Ludwig Friedlander. Barnes & Noble, Inc. ($27.50). A four-volume reprint of the seventh edition of Friedlander's great contribution to classical study. This translation into English by Leonard A. Magnus was first published in Britain in 1907.

THE STATESMAN'S YEARBOOK: 1965–66, edited by S. H. Steinberg. St. Martin's Press ($10). For the updated version of this standard work the editor has included such material as details of the newly independent states of Malta, Malawi, Zambia and Gambia, and other political, economic and statistical data.

FROM ZERO TO INFINITY, by Constance Reid. Thomas Y. Crowell Company ($3.95). For this third edition of Miss Reid's sprightly popularization of the elements of number theory she has added a new chapter on the famous transcendental number *e*. Of the many books that roam this field Miss Reid's is one of the best.

AUFGABEN UND LEHRSÄTZE AUS DER ANALYSIS, by G. Pólya and G. Szegö. Springer-Verlag ($18). A two-volume reissue of Pólya and Szegö's highly regarded collection of problems and theorems of mathematical analysis.

STEEL RAILS TO THE SUNRISE, by Ron Ziel and George Foster. Duell, Sloan and Pearce ($12.95). An attractive photographic essay about one of the oldest railroads in the country: the much used, much berated, much neglected, inevitably nostalgic Long Island line that runs—when it runs—from Pennsylvania Station in New York City to the sandy hills of Montauk.

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